

STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

EVOLUTION OF THE CALIFORNIA LANDSCAPE

BULLETIN 158



1952

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

Kim

Kim McKellar



Digitized by the Internet Archive
in 2023 with funding from
Kahle/Austin Foundation

<https://archive.org/details/evolutionofcalif0000norm>

EVOLUTION OF THE CALIFORNIA LANDSCAPE

By NORMAN E. A. HINDS

Associate Professor, Department of Geological Sciences
University of California, Berkeley, California



EVOLUTION OF THE CALIFORNIA LANDSCAPE

BY THOMAS A. HARRIS

Author of "The Evolution of the California Landscape"
and "The Evolution of the California Landscape"



First Printing, 8M, 1952
Second Printing, 3M, 1957
Third Printing, 3M, 1960

LETTER OF TRANSMITTAL

TO HIS EXCELLENCY

THE HONORABLE EARL WARREN

Governor of the State of California

DEAR SIR: I have the honor to transmit herewith Bulletin 158, *Evolution of the California Landscape*, prepared under the direction of Olaf P. Jenkins, Chief of the Division of Mines, Department of Natural Resources. This volume is profusely illustrated with photographs, maps, and drawings, characterizing the significant surface features of the entire State. The author, Professor Norman E. A. Hinds of the Department of Geological Sciences, University of California, has systematically described those surface features as they are related to the geology and rock structures of the State, and has shown how these features have developed through natural processes operating over the long periods of time required to produce California's diversified landscape.

Bulletin 158 should find a useful place in the schools of the State and among those persons who love to travel and admire California. It should help to increase enjoyment of what is to be seen by explaining thoroughly why the surface features are what they are.

Respectfully submitted,

WARREN T. HANNUM, Director
Department of Natural Resources

APPROVED:

W. T. H.

November 17, 1952



FRONTISPIECE. Sierra Nevada west of Bridgeport, Mono County. *Photo by C. W. Chesterman.*

TABLE OF CONTENTS

	Page
Introduction	7
Sierra Nevada	11
Basin-Ranges	61
Mojave Desert	87
Colorado Desert	97
Modoc Plateau	109
Cascade Range	117
Klamath Mountains	137
Great Valley	143
Coast Ranges	155, 231
Transverse Ranges	183
Peninsular Ranges	195
Sea Floor	217
Index	233

INTRODUCTION

INTRODUCTION

California may be divided into a number of units called *geomorphic provinces* (the Sierra Nevada, Basin Ranges, Mojave Desert, Colorado Desert, Modoc Plateau, Cascade Range, Klamath Mountains, Great Valley, Coast Ranges, and Transverse Ranges geomorphic provinces shown on plate 2), each of which is characterized by a distinguishing geological record, particularly in the later part of earth history, and by more or less uniform relief features or combinations of features throughout its area. These geomorphic provinces are remarkably diverse, and in the midst of some of them great numbers of people live; others, more distant, are visited by an increasing host each year. Frequent requests are made for the geologic story of Yosemite Valley, Lake Tahoe, Death Valley, Mount Shasta, the great ranges extending eastward from Los Angeles and the bold shore features of California. As with music, literature, the arts, or anything else, the more one understands about what he is hearing, reading, or seeing, the more interesting it becomes. So far no book has been written which tells the story of the evolution of California's landscape. There are technical papers and reports about many areas, but they are in the language of the scientist, much of which is like a foreign tongue to the layman, and they contain a great amount of information of interest only to the specialist on the subject. Therefore, in this volume an attempt is made to bring together information about the various parts of the state in a fashion which those uninitiated in the complex vocabulary of geology can understand. The book is not intended for the trained geologist, but for the layman who wants to learn more about places he has seen or may see. Included are abundant pictures, sketches, and diagrams, for these often make clear what written words can not. Furthermore, the illustrations may awaken many people to the myriad of scenic wonders lying within California's boundaries, wherein is perhaps the most remarkable collection of natural masterpieces to be found in any state of the Union.

Because of California's huge area, studies of many parts are incomplete or not even made, so we have only a partial picture of how the landscape reached its present form; none the less, enough information is available so that all of the major divisions can be described in general outline at least. The state is so large and its geological history is so complex that no single person can know by any means all of it, for field study is slow. Therefore it has been necessary to draw freely on the writings of others. In order to avoid referring to so many writers in the text, practically all names have been omitted, but the significant publications have been listed at the end of each chapter. By these lists acknowledgment is made of use of information which

many workers have gathered; they serve as sources for further reading for any who are particularly interested in a certain section.

The following books give fundamental presentations of landscape evolution; the first three are intended for elementary college courses in the subject and for the lay reader; the last three are somewhat more advanced.

- Hinds, N. E. A., *Geomorphology*, Prentice-Hall, Inc., New York, 1943.
- Lobeck, A. K., *Geomorphology*, McGraw-Hill Book Company, New York, 1939.
- Worcester, P. G., *A textbook of geomorphology*, 2d ed., D. Van Nostrand Company, 1948.
- Cotton, C. A., *Landscape*, 2d ed., Whitcombe and Tombs, Ltd., Wellington, N. Z., 1948.
- Cotton, C. A., *Geomorphology*, 5th ed., John Wiley and Sons, 1949.
- Von Engeln, O. D., *Geomorphology*, The MacMillan Company, 1942.

Geomorphology is the technical name for the scientific study of land forms and landscapes, being derived from three Greek words *ge-* earth; *morphos-* form; *logos*, science or study. In former years, this subject was termed *physiography* and a number of books, now largely out of date and mostly out of print, were written under this title.

The reference volumes listed above are well illustrated, so that they give the reader an excellent pictorial view of the earth's land forms, as well as descriptions of their origin.

For those who are particularly interested in rocks and minerals, the following books of rather popular nature are suggested:

- English, G. L., *Getting acquainted with minerals*, Mineralogical Publishing Co., Rochester, N. Y., 1934.
- Fenton, C. L., and Fenton, M. A., *The rock book*, Doubleday and Company, Inc., New York, 1946.
- Hurlbut, C. S., and Dana, E. S., *Minerals and how to study them*, John Wiley and Sons, Inc., 1949.
- Murdoch, J., and Webb, R. W., *Minerals of California*, California Division of Mines Bull. 136, 1948.

The Earth's Age

Although the age of the earth has been a much-debated topic for centuries, recent improvements in scientific tools have allowed a more accurate estimate to be made now than ever before. With the advent of our knowledge of *radioactivity*, a new means for determining the age of some earth materials was evolved, and the findings enormously expanded the known length of earth history. *Radium* is an element developed by the natural breakup of atoms of parent elements like *uranium*, *thorium*, and *actinium*, which are contained in a few minerals of the earth. During the disintegration of the atoms, the valuable gas *helium* also is generated. Radium itself decomposes into other elements, so that we have a *radioactive series*. The final product of this natural change seems to be one of the isotopes of *lead*. *Isotopes* are varieties of elements having the same atomic numbers, virtually

the same chemical properties, but differing slightly in atomic weights. The lead-isotope formed from decay of parent radioactive elements apparently does not break up, and the rate of decomposition has been accurately measured in terms of the *half period of decay*. Therefore if an uranium- or thorium-bearing mineral is present in a rock, the ratio of the uranium and thorium content and the helium and lead isotope content can be determined. Only minerals from fresh or relatively fresh volcanic rocks can be used, for in these alone the significant mineral grains have been altered or disturbed to the least extent and material of mixed source is not present. Certain corrections have to be made to allow for changes which have occurred since the mineral was formed so that the calculations are complicated. Helium seems less satisfactory for the determinations than lead, probably because it can escape more easily from rocks than the solid element. The oldest known minerals come from Russia and Manitoba, Canada; their ages are 1,850 and 2,300 million years respectively. Because volcanic rocks have been erupted at various places over the earth or emplaced below its surface during the entire known history, an approximate time scale has been set up. This undoubtedly will be made more accurate and fuller as techniques are improved and more determinations of mineral age are made.

There are serious discrepancies between determinations based on helium and those based on radio-lead, but, in spite of this, all measurements so far made indicate that the recorded history of the earth probably exceeds a billion and a half years. Back of this known record there is a long interval, perhaps a half billion or more years, from the earth's origin to the formation of the oldest known rocks. The age of the earth thus is between two and three billion years.

To facilitate discussion of events which have taken place over this immense span of time, it has been divided into major units called *eras*; these are composed of briefer intervals termed *periods*, which in turn are separable into still shorter time units known as *epochs*. The passage from one geological era to another has been marked by many profound changes. Over long intervals, but short as compared with the length of the era, the continents have grown very large, and mountain ranges have been built in various parts of the earth. Circulation of the ocean and the atmosphere has been conspicuously altered by these geographic changes, with consequent important climatic modifications. The changes between periods and epochs are less pronounced. For example, an era, called the *Mesozoic*, ended about 60 million years ago as the result of such events as are described above, and a new one, the *Cenozoic* was initiated. We live in the latter era, which is composed of one period, the Tertiary, and this period is divided into five epochs, the Eocene and Oligocene, or early Tertiary, including 40 to 43 million years, and the Miocene, Pliocene, and Pleistocene, or late Tertiary, covering 15 to 17 million years. The

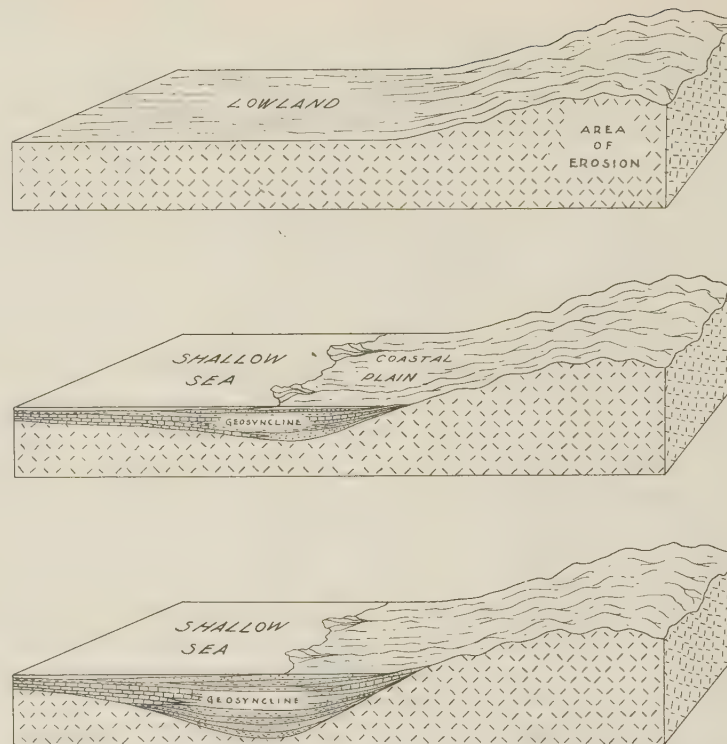


Diagram showing three stages in the evolution of a geosyncline. *Top:* Highland and adjoining lowland. Sediment transported from the erosion area is deposited on the lowland. *Center:* Lowland invaded by shallow ocean. Floor of the basin subsides under load of debris. *Bottom:* Trough-like depression called geosyncline is formed by continued deposition. Strata may be tens of thousands of feet thick in center of geosyncline. See p. 15. N. E. A. Hinds, *GEOMORPHOLOGY* (copyright 1943, by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

Pleistocene epoch commenced one or two million years ago, and is one of the most remarkable interludes of earth history.

The following discussion of the landscape of California is concerned principally with events which took place during the Cenozoic era; but some dating as far back as the Jurassic and Cretaceous periods of the Mesozoic era also are of great significance. Mesozoic time is divided into three periods, the Triassic (which represents about 30 million years), the Jurassic (40 million years), and the Cretaceous (55 million years) closing the era. Each of these periods left an imposing record in various parts of the state. In landscape evolution, the first imprints recognizable in California today were made in Jurassic time, when the ancestors of the Klamath Mountains, the Sierra Nevada, part of the Transverse Ranges, the Peninsular Ranges, and some other ranges appeared.

SIERRA NEVADA



FIG. 1. Sierra Nevada, showing Junction Peak and Diamond Mesa. *Photo by George J. Young.*

SIERRA NEVADA

Hugest of the mountain ranges in California and one of the most massive in North America is the Sierra Nevada, which lies along a considerable stretch of the eastern boundary of the state. In length the range measures about 430 miles, in width from 40 to 80 miles; a goodly number of its peaks exceed an elevation of 12,000 feet above sea level, and Mount Whitney (14,496 feet) is the highest spot in the United States. Dr. F. E. Matthes of the United States Geological Survey, who for many years studied Sierran geology, states that "the range stands higher above its immediate base than any other" in the country. "The Rocky Mountains, many of whose summits rise above 14,000 feet, stand only 9,000 feet above the Great Plains to the east which attain altitudes of about 5,000 feet at the foot hills; but the Sierra Nevada stands not less than 11,000 feet above Owens Valley at its eastern base and 14,000 feet above the Great Valley of California at its west base."



FIG. 2. Cross section of the Sierra Nevada, California, through Mt. Whitney, its highest peak. The boundary fault system along which the range has been elevated by tilting is shown on the right-hand side of the section. In this part of the range, most of the rock exposed at the surface is granite, but there are considerable areas of the intensely folded and faulted bedrock into which the granite was intruded. After F. E. Matthes, *U. S. Geol. Survey Prof. Paper 160*, p. 25.

Most of the range trends slightly west of north, but at the southern end the direction changes to west of south. Strikingly contrasted are the two slopes: that to the west of the crest is broad and gentle, but that to the east is much more steeply inclined. Because of this unsymmetrical cross section, the crests of high peaks lie only a few miles from the eastern boundary of the Sierra Nevada, but from 30 to 70 miles from the western base. At the northern end of the Sierra, peaks of highest elevation are between 6,000 and 7,000 feet; near Lake Tahoe, Pyramid Peak, Mount Tallac, and other mountains in the vicinity are 9,000 to more than 10,000 feet high; in Yosemite National Park, the peaks reach 12,000 to 13,000 feet in elevation; and in Mount Whitney region the highest peaks are found—Mounts Williamson (14,384 feet) and Langley (14,042 feet), and, of course, Mount Whitney itself (14,496 feet). Farther south elevations decrease to about 6,500 feet where the Sierra Nevada province adjoins the California Coast Ranges near Tehachapi Pass, nearly 100 miles from Mount Whitney.

Because of the gentle ascent from the Great Valley, the western side of the Sierra Nevada does not present a particularly imposing spectacle, though the crest peaks, in the highest part of the range, stand out in striking fashion. Part of the eastern side, on the other hand, is one of the most imposing mountain escarpments in the world. The northern section is not impressive, for it is lower and is split into minor ranges branching off in a northerly direction from the main range. From near Lake Tahoe southward the east front is higher and less broken. It rises about 6,000 feet above Mono Lake, 10,000 feet at the head of Owens Valley west of Bishop, and more than 11,000 feet near Mount Whitney. Then as the range decreases in height farther south, the escarpment lowers. In the Owens Valley section in particular, the eastern face appears to be an almost vertical declivity towering above a rather even lowland. This illusion is dispelled, however, by actual measurement of the slope of the front which in few places exceeds 25 degrees. The highest section is immediately west of Lone Pine. From there Mount Whitney is visible, but elsewhere in Owens Valley this peak cannot be seen since it is located at the head of a great canyon far back from the main front. The most conspicuous peak seen from Owens Valley is Mount Williamson, which stands out because of its particularly ragged form and its position more than a mile to the east of the main divide. Mount Langley is a somewhat lower peak but also presents an imposing appearance; Lone Pine Peak (12,951 feet), which stands about 2 miles east of the main crest, rises directly above Owens Valley, and appears to be even higher than Mount Whitney.

Climate

Since the Sierra Nevada parallels the Pacific coast, it forms a gigantic barrier lying athwart the path of the prevailing westerly winds, which most of the time carry moist air from the Pacific Ocean over the continent. The Coast Ranges farther west are too low to rob the air currents of much of their moisture except at their northern end where rainfall is heavy. As the winds ascend Sierran slopes to elevations where temperatures are lower, condensation gives abundant winter and spring snow and rain. Most of the precipitation falls on the western side increasing rapidly from about 4,000 feet and decreasing above 6,500 feet, according to the U. S. Weather Bureau, though Dr. Matthes puts the limit of heavy snow and rain at 9,000 feet. Below 4,000 feet the climate is semi-arid but less dry than in the Great Valley to the west. Above 9,000 feet it also is relatively dry because of the heavy extraction of moisture below that level; however, snow hangs much later in the year on the higher peaks because the longer duration of cold weather retards melting, the snow disappearing in June, July, or even August, and returning commonly in October.



FIG. 3. East face of the Sierra Nevada as seen from Owens Valley. The boundary fault system lies immediately at the base of the range. In the foreground is part of the Owens Valley graben. Erosion has modelled the scarp into a series of deep canyons, most of which are glaciated in their upper parts, separated by steep-sided narrow-crested ridges. Photo by W. C. Mendenhall, courtesy U. S. Geological Survey.

Within the zone of heavy precipitation, depth of winter snow exceeds that in any other part of the United States except the Olympic Mountains in northwestern Washington, the northern part of the Cascade Range farther east in the same state, and perhaps certain sections of the Rocky Mountains. Between elevations of 6,000 and 7,000 feet along the Southern Pacific Railroad, the annual snowfall amounts to 30 or 40 feet with as much as 60 feet falling in some years; at Norden Station (elevation 6,871 feet) the average yearly fall over a 34-year period is 34 feet. At Tamarack in Alpine County (elevation 8,000 feet), 73.5 feet of snow fell in 1906, the greatest amount ever recorded for the entire Sierra Nevada. Frequently there are 10 to 12 feet of snow on the ground at a single time and in protected spots the pile may reach 30 to 40 feet deep. Again at Tamarack during the winter of 1906-07, 8.8 feet of snow fell during a single storm, another record for the whole of the range.

Because the winds lose so much of their moisture as they travel up the western slope, relatively little passes to the eastern side, though considerable snow does accumulate at high elevations on account of the long duration of the cold. As the winds descend the east slope, they are warmed and consequently are able to evaporate moisture from the ground. The lower eastern slopes therefore are quite arid, except in the section near Mono Lake where the range base stands 7,000 feet and more above sea level. In the northern Sierra Nevada, the crest is considerably lower and more moisture is carried over to the eastern side, though again the lowest slopes are quite dry.

Dry summers are characteristic of the range. Little rain falls for periods of two or three months, but occasional thunderstorms occur, which generally are of short duration.

Most of the streams draining the range run roughly at right angles to its trend, that is, they flow south of west on the western side and north of east on the eastern side. There are some exceptions; for example, part of the course of the upper Kern River, the head of the Middle Fork of the San Joaquin River, Granite Creek and Chiquito Creek which parallel the crests of peaks. Because the divide between the eastward and westward flowing drainage is roughly the crest of the range, eastern streams are short and western are long; most of the eastern streams are comparatively small because of less available supply of water, and most disappear either within the lower parts of their canyons or very quickly after they emerge onto the desert basins at the base of the range. The principal exception is the Truckee River, flowing from Lake Tahoe and emptying into beautiful Pyramid Lake which lies in a desert basin more than 30 miles northeast of Reno. Some streams flow into Mono and other lakes in the section where the range base is at highest elevation, and Owens River, fed by Sierran tributaries, flows southward into Owens Lake.

The heavy concentration of precipitation on the western slope of the Sierra Nevada gives its streams much greater volume, though there is notable fluctuation caused by the dry season during summer and fall. The western streams, with the exception of the Kern River, are tributary either to the San Joaquin River in the southern part of the Great Valley or to the Sacramento in the northern part. These two trunk rivers join not far from Carquinez Strait, the single opening in the mountainous rim surrounding the Great Valley, and flow into San Francisco Bay. The Kern River is kept from joining the San Joaquin by a great barrier of sediment in the southern part of the San Joaquin Valley and flows into Tulare basin formerly occupied

by a large, shallow lake, most of which has been drained to develop agricultural land.

The principal rivers flowing down the western slope, named in order from south to north, are the Kern, Kaweah, Kings, San Joaquin, Tuolumne, Stanislaus, Mokelumne, American, Yuba, and Feather. In the upper reaches of the range, these streams are formed by the union of large as well as small tributaries, so that we find the Middle and North Forks of the Kings, and similar divisions of the others.

Because of the high elevation of the Sierra Nevada and sufficient slope in both directions from it, the main streams and their tributaries have cut narrow canyons. On the eastern side, the gorges are deep to the base of the range, but on the western side, the lower part of the range has quite gentle slope and consequently valley depth becomes much less. Some of the canyons in their headward parts range from 2,000 to 7,000 feet deep. The Tuolumne and the Kern, for example, are 4,000 to 5,000 feet deep in places, and the Kings and some of its tributaries measure 6,000 to 7,000 feet. On the western slope, the canyons are separated by considerable stretches of rolling upland, while between the gorges cutting the steeper eastern side, there are sharp-crested, narrow ridges.

Evolution of the Mountains

Mountains and mountain ranges are evolved in four principal ways: (1) by deformation, which is responsible for the principal eminences of the continents and larger islands; (2) volcanic action, which has produced some of the most conspicuous and splendid peaks of the lands and the only type of mountains rising above sea level from the floors of the very deep oceans; (3) erosion; and (4) deposition. Volcanic mountains are formed either by deformation of the surface as volcanic rock is forced into the outer part of the earth, or by eruption, which builds volcanoes and plains on the surface. Streams are principally responsible for erosion mountains, which in regions high above sea level may be mighty features of the relief. Deposition mountains are better termed hills and ridges; generally they are quite low, though some sand dunes rise a thousand feet above their base.

In terms of the length of earth history, mountains and mountain ranges, the most conspicuous features of the landscape, are relatively ephemeral, being built at various times and then destroyed. At many places in the earth, there is record of ranges great and small which have been worn down to rolling plains, with perhaps a few higher eminences, and then buried by hundreds of feet of debris deposited partly below and partly above sea level. The development of principal mountain ranges either by deformation or volcanic action is a revolutionary event because of the profound changes in rocks, rock structures, and relief which take place; but, as with all revolutions, many or most of their effects are later wiped out. From time to time parts of many ranges may be rebuilt and their span of life thus increased, but finally

even these rejuvenated sections are subdued and their former presence is proved only by certain rocks and rock structures which remain.

Deformation mountains are of three types, the principal being *fold-fault ranges* evolved by compression of long, narrow belts of the earth's rocky shell with consequent abundant folding and faulting. The major and most of the minor ranges of the continents and large islands are of the fold-fault variety, and some very important groups rise from the floor of the shallow ocean, as for example the great island galaxy off the west shores of Asia and Australia. Also, there are *fold mountains*, which are more or less simple anticlinal domes, usually of small size and moderate height, like the Kettleman and Elk Hills in the southwestern San Joaquin Valley. *Fault mountains* are blocks of the rocky shell bounded by faults along which they have been elevated, generally with some tilting.

The Klamath Mountains, the Sierra Nevada, the Transverse and Peninsular Ranges, and ranges of the Basin-Ranges province of eastern and southeastern California were originally fold-fault mountains, but they were built so long ago that they have been re-elevated on various occasions after erosion had greatly modified their initial topography. The Coast Ranges, on the other hand, are fold-fault mountains which have been created during the last half million or million years.

Evolution of the Sierra Nevada started perhaps 120 or 130 million years ago, when, in the late part of the Jurassic period, the western half of a great debris-filled trough or *geosyncline* was crumpled into mountains. The oldest rocks known from the Sierra Nevada belong to the Silurian period and are about 330 million years old; but there is plenty of indirect evidence, though not in the Sierra itself, which suggests that the geosyncline existed long before. The youngest formations involved in the deformation are late but not latest Jurassic, and were laid down in an ocean. Therefore it is quite possible that the first ridges of the ancestral Sierra Nevada appeared as islands projecting above this sea and later were welded into more continuous land. Compression was intense, so that once-horizontal layers are now steeply inclined and broken by great numbers of faults. Magnificent sections of the formations showing both sedimentary and volcanic rocks may be seen along Highways 40 and 50 traversing the Sierra Nevada, along Highway 24 following the canyon of the Feather River, and along Highway 120 leading from Mariposa to Yosemite National Park. There are of course good sections in many other places, most less accessible.

How far the belt of Jurassic deformation extended is not definitely known. Some believe that it included most of California, western Nevada, Oregon, Washington, and much of British Columbia, even extending into Alaska and Lower California. Others think that considerably less territory was affected. Much of the belt has been very deeply eroded since the deformation, covered by deposits of later age, and broken to pieces by more modern faulting.

Those who have studied the Sierra Nevada think that the Jurassic fold-fault mountains were not particularly high—perhaps 6,000 or 7,000 feet maximum.

Prior to the building of the Sierra Nevada fold-fault ranges very different geography existed. West of the present California coast there was a long land area or series of land areas known as Cascadia which extended for some distance into the eastern part of what is now the Pacific basin. Until late in Cenozoic time, Cascadia was the principal erosion area in this part of America, for it stood higher than most of the land stretching off to the east. This picture strikingly contrasts with that of the present, for Cascadia no longer exists and the great mountainous belt from the Pacific Coast to the Rockies has become the principal center of erosion. Streams flowed down the eastern slope of Cascadia either across lowlands which lay at its base or into shallow oceans which spread from time to time over these plains. For a very long period, the low country fronting the land now gone was a basin of deposition, though at times accumulation of sediment was interrupted and erosion modelled the deposits which had formed. Also there were important volcanic cycles when immense quantities of lava were poured out and fragments were violently blasted from volcanoes. Part of these eruptions occurred below sea level and part above. This complex history is recorded in the multitude of rock layers and rock masses found in the mountain ranges of the state; the time involved extended from before the beginning of the Paleozoic era to the end of the last epoch of Cenozoic time, very likely including more than a billion years.

Probably a shallow trough-like depression was first formed by deformation along the margin of the Cascadian highland. This depression was enlarged and deepened by the load of sediment accumulated within it, which generated stresses in the weak zone below the crust, causing solid outflow of material from beneath the belt of maximum deposition. Eruption of volcanic material onto the surface within this belt also aided evolution of the trough. Eventually thousands of feet of sedimentary and volcanic deposits were formed. The sediments and remains of life buried within them show that most of the deposits were accumulated under the ocean which in few places was deeper than 600 feet at any time and over most of its extent was much shallower. From this evidence it is clear that, while the base of the trough sank many thousands of feet (the total thickness of the deposits is not known but certainly exceeds 30,000 feet in many places), the upper surface when below sea level sloped gently from the water's edge to very shallow depths. This was part of the *continental shelf*, which is the continuation of land under the ocean to where slopes increase and lead to the floor of the deep ocean. When the shelf rose above sea level, it rarely stood more than a few hundred feet high. A sediment-filled

trough of huge dimensions evolved in the fashion described above is called a *geosyncline*.

Over the continental interior east of the geosyncline deposition of sediment was much lighter and the surface of the rocky shell in consequence was not depressed so far.

As weathered rock was removed from Cascadia, that land was gradually lowered, but from time to time, deforming forces elevated it, accelerating the erosive processes and increasing the ruggedness of its relief. Some sediment came into the geosyncline from other bordering lands, but the coarseness and mass of the deposits adjacent to Cascadia clearly prove that region to have been the prime source of the debris.

Geological evidence shows that accumulation of sediment and volcanic material in a geosyncline continues, though not without interruptions, for tens or even hundreds of millions of years. Fossils present in strata in the Sierra Nevada and in other California mountains clearly show a span of about half a billion years, and there are rocks long antedating these strata containing indirect evidence of life but no actual fossils. Deposition in a geosyncline is always voluminous but never continuous. From time to time the sea bottom is lifted out of the ocean to form low plains which suffer some erosion though they also may receive a veneer of continental sediment or volcanic rocks. Proof of such interruptions is clearly shown in breaks separating the various formations exposed in the mountains.

Although deposition in a geosyncline may go on for an immensely long period, it eventually ends; these troughs are weak belts in the crust because they contain so much unconsolidated or poorly consolidated debris and consequently they are rather easily deformed. Eventually the trough yields to the stresses constantly at work in the earth and begins to buckle and break. In a large section of California this happened more than a hundred million years ago. The rocks were folded into great arches called *anticlines* and troughs called *synclines*; also they were broken apart by faults of various sizes along which minor or major dislocations occurred. The architecture of the earth in this region was revolutionized, for, previous to the deformation, most of the rocks had been more or less nearly horizontal sheets. The growing ridges were upfolds and blocks bounded by faults and between them lay basins or troughs which were downfolds and fault blocks. Such a mountainous complex is called a *fold-fault system*. Sections which have been re-elevated in recent time are the Klamath Mountains of northwestern California, the Sierra Nevada, part of the Transverse Ranges east of Los Angeles, the Peninsular Ranges in the southwest corner of the state, and some of the fault block ranges lying beyond all of these mountains and extending across the Nevada border.

The deformation of this belt did not proceed without interruption, for there were times of greater activity separated by times of relative quiescence. None the less, over a relatively short geological interval—a few million years—in the later part of the Jurassic period, the building of the initial ranges was completed. The height of these mountains is not known, but it was considerably less than that of the highest part of the Sierra Nevada today; the principal peaks may have stood 6,000 to 7,000 feet above sea level but probably not much more.

During the disturbances resulting in the deformation of a geosyncline into mountains, major changes go on within the heart of the folded belt. Not only are the rocks bent and broken by the stresses exerted upon them, but those at some depth below the surface are metamorphosed; that is, they are partially or completely recrystallized, and new minerals and structures develop. Furthermore much igneous activity is initiated. The igneous mechanism is extraordinarily complicated and may be contained entirely below the surface as appears to have been the case during the deformation which produced the Jurassic mountains in California. There is no field evidence so far discovered that surface eruptions took place during this time, although there had been many before the folding began. As has happened in so many similar settings, an enormous body of *granitoid rock* developed a mile or more below the surface. The folded belt undoubtedly was invaded by liquid rock which evolved at still greater depth, but considerable sections of the granitoid mass appear to have been formed by the remaking of other rocks by volcanic gases and solutions into new material which cannot be distinguished from that formed during the crystallization of a molten mass. This process of remaking other igneous* and sedimentary rocks into rocks definitely of granitoid character is called *granitization*.

Igneous action, like deformation, was not continuous but rather occurred in a series of waves, for many bodies of granitoid rock have been differentiated in the Sierra Nevada, all apparently belonging to the same volcanic cycle. Some bodies transgress others, showing that they are slightly younger. In other words, the total body which is called a *batholith* or deep-seated igneous intrusion, was formed over a considerable time and consists of many parts, only a few of which have so far been separated.

Granitoid rock like that composing the Sierran batholith includes true granite and other rocks closely associated in chemical and mineral composition. They have been formed probably at depths of at least a mile below the surface. For this reason the growth of crystal grains has been relatively slow and the rocks are generally medium- to coarse-grained. They are characteristically light colored, gray being the

dominant shade. The rocks are made to a very large extent of two light-colored minerals, one called *quartz* and the other *feldspar*. Quartz is a mineral of simple composition, always being composed of one part of silicon and two parts of oxygen; feldspar, on the other hand, is represented by several varieties, each much more complex in composition than quartz. In most granitoid rock, there is a distinctly minor quantity of the dark-colored mineral grains that give the rock its pepper-and-salt appearance. These dark-colored minerals contain various proportions of iron and magnesium while the light-colored varieties do not.

The volcanic cycle apparently started during the deformation in the late Jurassic and continued after it, possibly into the earlier part of the Cretaceous period. When finished, a gigantic rock complex was evolved entirely under the surface. It probably extends throughout the folded belt and, in the Sierra Nevada at least, evidence derived from study of earthquake waves indicates that it is 10 to 12 miles thick. Round about the margins of this great mass, the covering rocks were intensely metamorphosed into new types, the metamorphic effects decreasing with distance from the batholith. The granitoid rock is very resistant as are most of the metamorphic rocks. Closer to the surface where the metamorphism did not reach and where the rocks of the geosyncline were less thoroughly consolidated, the materials were weaker and more easily weathered and eroded. The development of the granitoid core and its associated zone or *aureole* of metamorphic rocks thus increased the strength of the heart of the deformed belt.

The Sierra Nevada of today is very different and much more majestic than the ancestral ranges of Jurassic time. Instead of being a series of elevated ridges separated by troughs and basins, it is now a gigantic tilted fault block so huge that within it are a number of minor ranges, each of considerable magnitude. The eastern face of this immense block is a scarp developed along a multitude of fractures called *faults*. A fault is a break in the outer earth along which the adjacent blocks slip past each other. The western side of the Sierra Nevada is a complex of landscapes evolved during the long interval since the birth of the original fold-fault system.

Understanding of the many changes which have occurred in Sierran landscape requires a brief analysis of what has transpired since the mountains first appeared. Because the size of the range is so great and its geology so complex, at present it is possible only to outline the principal steps in the story.

Between the end of the first rise of the system and the close of Cretaceous time, nearly 60 million years elapsed, but of this interval there is only the scantiest record. By the beginning of the last or Cenozoic era, another 60 million years ago, the ranges had been so eroded that they were quite inconspicuous, and in places the ocean

* Igneous rocks have solidified from molten masses. Sedimentary rocks have been formed chiefly from waste products of other rocks or from organic debris, or by chemical precipitation in water.

spread to their western base. The land was so low that winds sweeping inland from the Pacific Ocean did not lose most of their moisture over Sierran slopes as they do today. Instead they provided enough rain for hundreds of miles inland to permit the growth of a luxuriant vegetation which could not possibly exist over most of the region under the arid conditions that now prevail. This is proved by the character of fossil plants found in deposits belonging to that time.

During the Eocene, first epoch of the Cenozoic Tertiary period, the region was bowed upward along an axis approximately that of the present Sierra-Cascade system. A low mountain barrier was created and fairly deep gorges were cut into the rising hills. The shore line still remained close to the present western base of the Sierra Nevada.

During Miocene time, however, the mountains had been elevated sufficiently to cut off most of the moisture and the region to the east became arid.

Much more vigorous disturbances marked the end of the Miocene and the beginning of the Pliocene epochs, for the Sierra Nevada was elevated considerably and became strongly unsymmetrical in form with a broad western and short eastern slope. There was much faulting and associated volcanic activity. Faulting conspicuously increased the boldness of the eastern slope, especially north of Mono Lake where several long range spurs were developed. Between one of these spurs, the Carson Range, and the main Sierra Nevada, a section sank, evolving the basin now partly occupied by Lake Tahoe. Faults also broke the western foothills, so that the long slope in places descends in a series of abrupt steps.

Then followed a period of relative calm during most of Pliocene time and erosion dominated over elevation by deformation. Considerable changes in the landscape of the range resulted. But the quiescence was not enduring, for at the end of the Pliocene and continuing into the earlier part of Pleistocene, the deformation was vigorously renewed. These movements lifted the Sierra Nevada approximately to its present height and the country to the east also was elevated so that Owens Valley stood about 9,000 feet above sea level, considerably above its present maximum height. Most of the elevation took place before the beginning of the Pleistocene or Glacial epoch so that the snow and ice which remained year after year was bulky enough to generate the slowly moving ice masses called *glaciers*. Records of profound glaciation recognized as belonging to the earliest part of Pleistocene time have been found, hence the region must have been nearly as high as now for, even during the climaxes of the glaciations, the snow line in the Sierra Nevada apparently did not lie much below 11,000 feet.

Most convincing evidence left by an early glacier is provided by the debris deposited on the mountains west of McGee Canyon. The

principal glaciers on the east side of the Sierra Nevada, because of the steepness of its slope, were *valley glaciers*, that is they formed in valleys or canyons which already had been eroded by rivers. Moraines are great heaps of unassorted rock fragments, some of which are very large. Valley glaciers leave two principal types, the more common *side moraines* formed from debris frozen in the sides of the ice and carried on its top, and *terminal moraines*, composed of rocks and fine sediment pushed in front of the ice and melted from its end.

The McGee moraine, which has been identified as belonging to the first of the four glacial stages, ends abruptly at the great eastern scarp, and stands about 3,000 feet above Long Valley at the base of the scarp. Study of the moraine shows that its glacier followed a rather flat, shallow valley high in the Sierra Nevada, proving that McGee Canyon and the scarp into which it has been cut did not exist. Moreover the McGee moraine, in spite of some later damage, obviously was about as large as the moraines of the later glaciers. This, together with much other evidence, indicates that the Sierra Nevada had about as large an ice mantle during the early Pleistocene as it did later in the epoch.

Abundant evidence indicates that the eastern scarp does not owe its height to elevation along faults at the base of the range. Rather, long, narrow blocks sank, developing Owens, Carson, and other valleys immediately east of the range. These depressed masses were broken into great numbers of fragments by lesser faults and along them there has been much volcanic eruption. On the other hand there is not much evidence of shattering within the main mass of the Sierra Nevada at the time of the last disturbance.

Other proof that the depressed blocks have sunk is afforded by the slant of the lowlands toward relatively fresh fault scarps. At the base of the range and against these scarps is either wet, swampy land or lakes, such as Owens Lake, which is deepest near its western shore against the highest section of the Sierran scarp; the wet meadows sloping to the range base near Bigpine; Mono Lake, lying next to a steep scarp and deepest on its western side; the marshes in Carson Valley which lie directly beneath fresh fault cliffs at the base of the Carson Range; and Honey Lake at the far northern end of the scarp.

The giant scarp, without doubt the most magnificent example in America, thus is not much over 800,000 years old and has been increasing in majesty as the bordering, eastern blocks have continued to sink. It has been considerably battered, for a multitude of deep gorges have been cut into it and the upper parts or even the entire length of many of these gorges have been glaciated.

Faulting at the base of the range has occurred intermittently, some of it being very recent. Very probably there have been differential movements along the faults so that the Sierra Nevada has risen some-

what but its height has not been greatly increased over that developed by the late Pliocene-early Pleistocene deformation.

Farther east in the Basin-Ranges province, similar faulting separated formerly continuous stretches of landscape, raising some to form ridges and ranges, and depressing others to form troughs and basins. Some of this faulting to the east started as early as Miocene time, some is of much later, and some is going on actively today. Of the blocks which were isolated by faulting, the Sierra Nevada is by far the largest. It must not be supposed that the great fracture systems bounding the blocks were developed quickly or that the immense dislocations were accomplished in brief intervals. Rather, the faults grew in length and complexity and the individual movements along them were relatively small, a few feet to a few score of feet. Furthermore, there is no evidence that dislocations occurred along the entire length of a fault system at the same time.

There is much additional information about the growth of the Sierra Nevada contained in F. E. Matthes' entertaining book, *The Incomparable Valley*, compiled after his death by Fritiof Fryxell. Much of the foregoing story of the later history of the range is summarized from this volume.

As the up-arching of the Sierran region went on, the maximum elevation was attained in the northern half of the southern section. Very possibly this height is being slightly increased while the adjacent valley blocks are still sinking.

Eastern Fault Scarp

In places, as along most of the western side of Owens Valley, the principal fault bounding the eastern base of the Sierra Nevada appears to be relatively simple and most of the movement was concentrated along it. Along most of the range, however, intersecting fractures are indicated by salients and re-entrants like those west of Bishop near the head of Owens Valley. Also, there are many faults parallel to the main system along which blocks have sunk less than the valley blocks, producing a terraced front. South of Mount Whitney, there seems to be no actual evidence of faulting along the base of the range, but its form definitely suggests that this portion as well is a tilted fault block. The fracture zone appears to have been completely buried by great masses of sediment carried from canyons worn into the fault scarp. The faulting in this southern section appears simple for there is little evidence of the step-blocks that produce a terraced front.

The great scarp is highest and most clearly defined from Olancho at the southern end of Owens Valley to Independence, for the abrupt descent from the crest of the range is not broken by any foothills. Striking *faceted spurs*, the truncated ends of ridges broken by the faulting, may be seen south of Owens Lake but are larger and bolder southwest of Independence. The east slope of Mount Williamson, dominating peak of the Sierra Nevada visible from this part of Owens

Valley, is a huge triangular facet into which have been cut three lesser facets. Each of the three rises to a height of 10,000 feet, below which the range slope shows the marked over-steepening characteristic of recently developed fault scarps.

West of Independence, the Sierran scarp changes in contour. The base exhibits salients and re-entrants formed by granite foothills protruding through the deposits at the base of the range and apparently lying against its main mass along the principal fault system. These foothills doubtless are step fault blocks which either have not sunk as far as the Owens Valley graben or have not been elevated as far as the main block.

Farther north toward Bishop, fine triangular facets again appear indicating that the boundary fracture is a simple one. As far north as Birch Mountain, the eastern side of the Sierra Nevada presents unmistakable proof that it has been developed by profound dislocation along the fault system, but from there northward to Bishop Creek, the evidence is less convincing. Long, straggling foothills project into Owens Valley and merge with the main mountain mass. In this section, there probably are a number of parallel faults, with the dislocation distributed more or less equally along them through quite a wide zone. There has been sufficient erosion to obscure most evidence of faulting, a common occurrence where this step structure is present.

In the vicinity of Bishop Creek, the fault system is offset to the west about 8 miles in a manner characteristic of the area farther north. The scarp here shows the same abruptness and simplicity as near Owens Lake; the best development is the extraordinarily steep slope facing Round Valley. The fault indicated by this declivity, if prolonged southward, would coincide with the canyon of the South Fork of Bishop Creek, which is conspicuous among the canyons on the east side of the Sierra Nevada in having an approximately northward trend. There is good evidence that this canyon has been developed by faulting. The fact that an advanced erosion surface standing 2,500 feet above the river in the bottom of the canyon is at essentially the same elevation on both sides of the canyon indicates that this gorge, if evolved by faulting, is a *rift valley*: that is, its floor is a block which has sunk between two faults. An oiled road leads up this valley from Bishop to the beautiful glacial lake country on the east side of the high Sierra.

Multiple displacements along both sides of Truckee Meadows have formed this *graben*,* which has hill areas projecting above its surface.

North of the Truckee River, the faulting and therefore the Sierran front change notably. Displacement along the boundary fault diminishes, the faulting apparently is multiple in many places, and northward-trending ridges project from the main mass of the range.

* A graben is a basin or trough formed by subsidence of a block or blocks of the earth's crust along faults.



FIG. 4. Lake Tahoe (background). Fallen Leaf Lake (left foreground) occupies a basin formed by a terminal moraine left by a valley glacier that came from the Pyramid Peak area. *Photo by courtesy U. S. Army Air Corps.*



FIG. 5. Section showing fault scarp north of Kern River, east of Bakersfield. After G. K. Gilbert, *U. S. Geol. Survey Prof. Paper 153*, p. 88.

Tahoe Basin

The outstanding example of the effect of faulting within the Sierra Nevada is the Tahoe basin, which lies near the crest in the central part of the range and is partly occupied by Lake Tahoe. This lake, by far the largest in the Sierra Nevada and the major body of water in the state, is nearly 22 miles long, 12 miles across at its widest place, and has a depth of more than 1,600 feet. Its surface stands a little over 6,200 feet above sea level. On the eastern and western sides of the basin are rugged mountains whose summits are from 8,000 to 10,000 feet high; Rubicon Peak (9,193 feet) and Mount Tallac (9,785 feet) are the principal eminences on the western rim. In the Carson Range on the east side, Mount Rose rises 10,800 feet and Genoa Peak 9,173 feet. This eastern range slopes less abruptly toward the basin than does its western counterpart and therefore looks lower, but it is not. The two ranges completely enclose the low region between.

It is the common belief of people living or visiting at Lake Tahoe that it is of volcanic origin, but such is not the case. The general features of its evolution are well known, though many details remain to be supplied. The basin has been formed by dislocations occurring at the time of the vigorous Miocene-Pliocene deformation. Two principal faults, one on the east and one on the west side of the basin and both roughly parallel to the great boundary fault system at the eastern base of the range, evolved as the Sierran region began its upward movement. The Carson Range, forming the eastern rim of Tahoe basin, rose along the boundary fault while the mountains on the west were elevated along the fault on that side. The intervening area slowly and unevenly settled evolving the Tahoe basin and Sierra Valley farther north.

Because of the heavy snows and rains in the region, a lake quickly formed near the southern end, or lowest part of the graben. Since the passes through the bordering ranges stand at considerable elevations above the basin floor, the lake grew to much greater size and depth than it now is. Finally its water found an exit through a low spot in the Carson Range not far east of the present site of Truckee and the Truckee River was born, pouring down the eastern slope of the Sierra Nevada. This stream began to excavate a gorge mostly in unconsolidated volcanic debris. Highway 40 follows the course of the Truckee River in going down the eastern side of the Sierra Nevada. As the canyon was deepened, the level of Lake Tahoe gradually fell and its area diminished.

Somewhat later basalt flows were erupted, flowing into Truckee Canyon and forming a dam extending to the present northern end of the lake which for a time broke the Truckee River. Finally the lake overflowed this barrier, cut a gorge through it, and the river was re-established; the flows of lava can be clearly seen in the walls of the gorge along the highway leading to Lake Tahoe from the north.

The Truckee River flows from its canyon at the eastern base of the Sierra Nevada across desert fault basins until it empties into Pyramid Lake which occupies one of these basins some 30 miles northeast of Reno, Nevada.

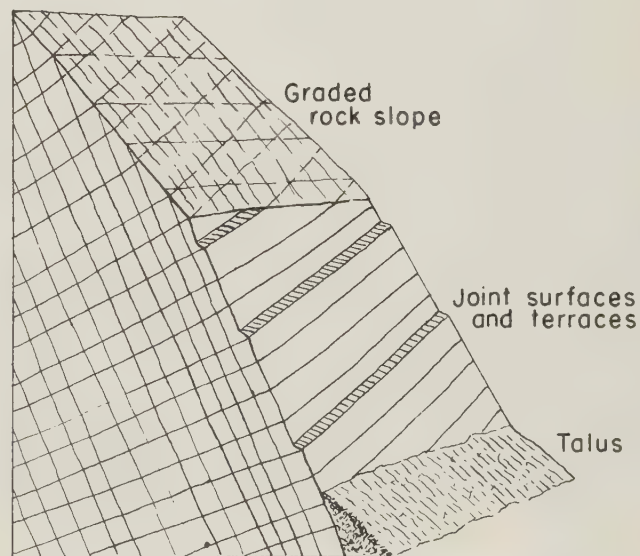


FIG. 6. Idealized sketch of the fault scarp which extends for about five miles north and south of the Kern River Canyon east of Bakersfield. After G. K. Gilbert, *U. S. Geol. Survey Prof. Paper 153*, p. 86.

The southwestern side of the Sierra Nevada is sharply contrasted in dimensions, slope and topography with the great scarp fronting in the opposite direction. Only in one place for a distance of about 5 miles north and south of the Kern River canyon east of Bakersfield in the San Joaquin Valley is the western base defined by a fault. Elsewhere, except for minor effects produced by faulting, the southwestern side slopes gradually to its base where it passes under sedimentary deposits which in places in the Great Valley to the west are very thick.

At the mouth of the Kern River canyon, the base of the Sierra Nevada is a nearly straight face of granitoid rock broken into triangular facets by young gorges which cut it. The scarp is about 400 feet high and 5 miles long. Actually it is not a single surface, but is made up of several steep declivities separated by narrow inclined terraces that evidently are controlled by jointing which is prominent in the bedrock. The steep sections of the scarp exhibit little evidence of faulting for they have been too much weathered. There does, however, appear to be a vertical grooving best seen at a little distance and many patches of small quartz veins are vertically fluted in harmony with the larger grooving. Probably the various elements composing the main scarp were originally a single fracture surface, and have since been separated by slippage along the joints, developing a minor type of step faulting. On the north side of the Kern River canyon, the lower part of the scarp is much steeper and smoother than the upper, indicating close approach to the slope of the actual fracture surface, the upper part having been more eroded.

The narrow terraces which break the continuity of the scarp are roughly parallel and rise from north to south across it. They are covered to some extent by soil and waste which has fallen from above. At the base of the scarp are considerable deposits from the face and brought out from the canyon of the Kern River. The fault evidently is recent but no movement is known to have occurred along it in historic time.

This rift certainly does not mark the western boundary of the Sierran block, rather it is a local feature. Location of the western boundary is not known but possibly it may be against the Coast Ranges on the western side of the Great Valley. It has been proved that Sierran bedrock extends under deposits in the Great Valley which in places are very thick, but the bedrock has only been met where the overlay of sediment is much thinner. As more deep oil wells are drilled and particularly as more geophysical prospecting is done in the Great Valley, knowledge of the extent of the Sierran block below the valley will be extended.

The foothills of the Sierra Nevada rise from the border of the Great Valley as a series of low hills and ridges increasing in altitude and elevation above their surroundings as the main range becomes higher.

The higher ridges in the foothill belt are formed by the more resistant members of the Sierran bedrock complex while the weaker members form low hills having rather gentle contours. Between these eminences are narrow ridges and winding valleys. East of the foothill belt, the ridges and hills are more prominent and the canyons are deep and narrow.



FIG. 7. Old erosion surface near Kaweah Canyon. Photo by Cordell Durrell.

Between the great canyons which are such prominent features of the western side of the Sierra Nevada are extensive stretches of rolling upland that become increasingly rugged in the higher parts of the range. In these uplands remnants of two principal landscapes so far have been recognized.

To understand the development of this ancient relief, it is necessary to trace changes which have occurred since the Jurassic fold-faulting. When the Sierra Nevada was first built, it consisted of a series of roughly parallel ridges separated by troughs or basins, all outlined by the deformation. The principal rivers flowed through these troughs, here and there breaking across or flowing around the ridges and eventually passing beyond the mountain belt. Minor streams descended the ridge slopes, either joining the trunk rivers within the range or flowing beyond the mountains to add themselves to other drainage. Such a stream pattern is found today in the Coast Ranges, which were formed by fold-faulting in middle Pleistocene time.

By the end of the Cretaceous period, the Sierra Nevada had been worn down to relatively low elevations so that its highest points were not much more than 2,000 or 2,500 feet above sea level. Early in the Eocene epoch, the range seems to have been gently upwarped along

an axis roughly coinciding with its present crest; whether a corresponding slope increase took place on the eastern side we do not know, for later events have obscured too much of the record. As a result, there was considerable rearrangement of drainage, for southwest-flowing streams grew at the expense of streams oriented in other directions, becoming trunk lines which divided among themselves many rivulets that had been flowing parallel to the trend of the range. In the latest part of the Eocene and part of the following Oligocene epochs, there was an alteration of erosion, deposition, and volcanic eruption which altered the landscape, but subsequent modifications have wiped out most of this record.

The Oligocene activity was followed by a long interval of virtually uninterrupted erosion which developed toward the end of Miocene time the older of the two landscapes found in the rolling country between the great canyons of the western slope. The highest peaks had been reduced to elevations of little more than 6,000 feet above sea level and were located principally where the crests of the Sierra Nevada are today; most of the peaks were aligned in roughly parallel rows as we now see them and these rows probably represented the greatly modified ridges formed during the Jurassic fold-faulting. In the northern part of the Sierra Nevada there are enough remnants of the deformed bedrock in many places to indicate this clearly. In the southern two-thirds of the range, however, erosion had removed the bedrock and was working in the great granitoid batholith below; nevertheless, the rows of peaks clearly show that their position is controlled by structural ridges which once lay above the batholithic mass.

The peaks of Miocene time were far from startling, rising only 1,500 to not much more than 2,000 feet above rather broadly flaring canyons that separated them. Their tops were mostly flattish or rounded and their slopes were only moderately steep. Farther down the western slope of the Sierra Nevada the landscape was still more subdued. Ridges from 500 to a little more than 1,000 feet separated flat valleys which increased in width toward the lower part of the range. The streams flowing in these valleys had reached maturity and had eroded terraces into the bedrock. Some of the ridges rose quite abruptly from the outer margins of the terraces while those in less resistant rock ascended with gentler slopes. Most of the streams flowed southwestward as they do today, but some followed depressions between the rows of peaks as they had done in the early stages of the development of the range. An example is the upper part of the Kern River which parallels the trend of the range between the eastern and western crests before it finally breaks across the latter to descend the western slope.

This stage in the evolution in Sierran landscape has been called the *broad valley stage*; remnants are recognizable in many places, par-

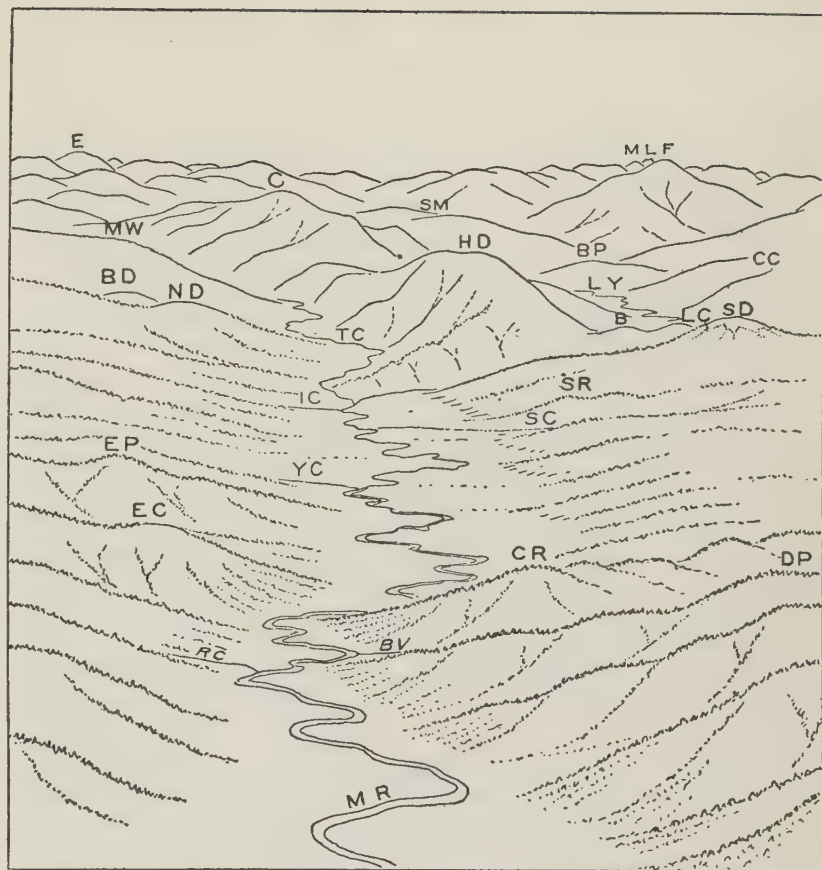


FIG. 8. Bird's-eye view of the Yosemite Valley as it probably was in the broad-valley stage, prior to the first great uptilting of the Sierra Nevada. The Merced River meandered sluggishly over a broad, level valley floor flanked by rolling hills between 500 and 1,000 feet in height. The crown of El Capitan stood about 900 feet high. There were no cliffs or waterfalls. The tributary streams all sloped gently down to the level of the Merced. The entire region was covered with dense rain-loving vegetation. RC, Ribbon Creek; EC, El Capitan; EP, Eagle Peak; YC, Yosemite Creek; IC, Indian Creek; R, Royal Arches; W, Washington Column; TC, Tenaya Creek; ND, North Dome; BD, Basket Dome; MW, Mount Watkins; E, Echo Peak; C, Clouds Rest; SM, Sunrise Mountain; HD, Half Dome; M, Mount Maclure; L, Little Yosemite Valley; B, Mount Broderick; LC, Liberty Cap; SD, Sentinel Dome; SR, Sentinel Rock; SC, Sentinel Creek; CR, Cathedral Rocks; BV, Bridalveil Creek; DP, Dewey Point; MR, Merced River. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 46.

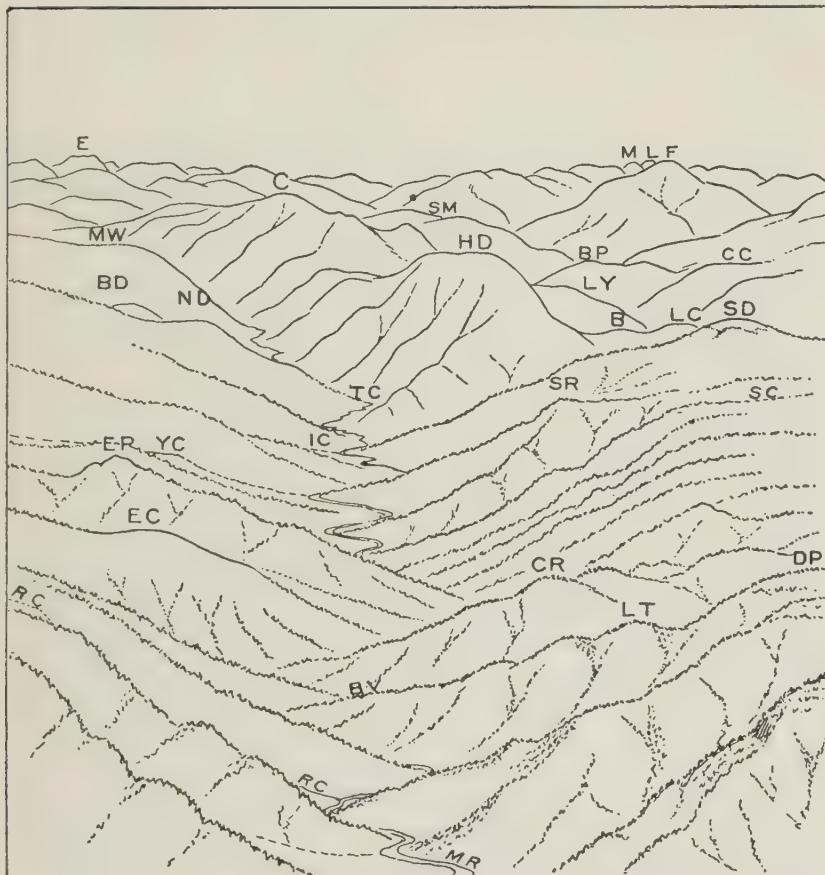


FIG. 9. Bird's-eye view of the Yosemite Valley as it probably was in the mountain-valley stage, after it had been deepened about 700 feet by the Merced River in consequence of the first great uptilting of the Sierra Nevada. The valley was flanked by uplands, and Ribbon Creek, Yosemite Creek, Sentinel Creek, Bridalveil Creek, and Meadow Brook cascaded steeply from the mouths of hanging valleys. Tenaya Creek, Illilouette Creek, and Indian Creek, however, had cut their valleys down to the level of the Merced. The region was covered with mixed forests containing sequoias. After F. E. Matthes, *U. S. Geol. Survey Prof. Paper 160*, p. 47.



FIG. 10. Bird's-eye view of the Yosemite Valley as it probably was in the canyon stage, just before it was invaded by the glaciers of the ice age. The valley had been cut 1,300 feet deeper by the Merced River, in consequence of the second great up-tilting of the Sierra Nevada, and had a V-shaped inner gorge and two sets of hanging side-valleys. Illilouette Creek and Indian Creek now also made cascades, but Tenaya Creek and lower Bridalveil Creek had cut gulches down to the level of the Merced. The region was covered with coniferous forests adapted to a temperate climate with cold, snowy winters. After F. E. Matthes, *U. S. Geol. Survey Prof. Paper 160*, p. 48.

ticularly in the southern part of the range. Naturally they have suffered much damage by later erosion and in parts of the Sierra Nevada have not been detected, though more thorough study may reveal them.

In late Miocene and early Pliocene time, the northern third of the Sierra Nevada at least became a great volcanic field. Frequent explosions erupted great quantities of coarse and fine debris of andesitic lava and a considerable number of flows also were poured out. Most of the centers of this activity lay east of the present Sierran crest but some have been recognized in the crest region. The fragmental deposits for reasons that we do not know became waterlogged and moved as great avalanches down the valleys piling one upon another as the volcanic cycle continued. Even after much erosion in the crest region there are sections of these volcanic mud flows 1,500 to 2,000 feet thick. In spite of the relatively low slope of the valleys, the mudflows were liquid enough to move through them and in some cases passed the base of the Sierra, spreading onto the eastern side of the Great Valley. The valleys in the range were well filled and some of the lower ridges were overwhelmed but the higher eminences projected above the volcanic surface. Apparently the mudflows formed a flat area with masses of bedrock protruding through it. Certainly this landscape covered much of the northern third of the Sierra Nevada but how far south it extended cannot be determined as the amount of erosion which has since occurred is difficult to estimate. The suggestion is strong, however, that most of the southern section of the range lay beyond the limits of the volcanic activity.

After the close of the volcanic episode in the earlier part of Pliocene time, the Sierra Nevada which then probably was much broader than today was elevated about 3,000 feet. The deformation doubtless was not continuous, but was concentrated in certain intervals with others of relative quiescence between. The elevation of course increased the slopes of the range and the streams were correspondingly invigorated. Where they had started to flow on the volcanic surface, they cut through it into the bedrock, while others in the broad valleys cut young gorges below the surfaces of the terraces which they had eroded prior to the elevation. These new canyons were 1,200 to 1,500 feet deep by late Pliocene time. The upper part of the Kern River, flowing parallel to the crests of peaks, reached maturity while the streams descending the steeper western slope were still young, at least throughout most of their length. The Kern therefore began to widen its valley, destroying much of the terrace which had been cut before the early Pliocene elevation. Remnants of the broad Miocene valley are preserved along the sides of the peaks of both eastern and western crests but are not particularly conspicuous; none the less it is possible to reconstruct the valley approximately. Remnants of the Pliocene mature valley are finely preserved as flat areas in the Mount Whitney

region. Thus there is striking contrast between this longitudinal mature valley and the dominantly young canyons of the same cycle on the western slope.

The Pliocene landscape, which is a much more vigorous one than the Miocene, has been termed the *mountain valley landscape*. The highest peaks of the Sierra Nevada at this time seem to have stood about 6,000 to 8,000 feet above sea level, but most of them had been evolved during the still earlier erosion cycle.

The late Pliocene and early Pleistocene elevation of the Sierra Nevada and the region to the east caused a sharp increase in the gradient of the streams and therefore in their downcutting power. They began the incision of the great canyons like the Yuba, the American, the King, and the Kern. Since the range probably is still rising to some extent, the canyons are still being deepened; they are narrow, V-shaped gorges with bold, ragged slopes rising abruptly from the sides of the streams, except where the canyon form has been modified by glaciation, as in Yosemite Valley. Although these great gashes have been speedily eroded because of the considerable increase in slope of the western Sierra Nevada and the abundance of water available, the elevation has been recent enough so that broad stretches of the older landscape remain between them, making it possible to read at least part of the chapters of later Sierran history. The canyons naturally are deepest in the central, highest part of the range; to the north and the south they are less conspicuous, but are nevertheless deep gorges.

This stage of landscape development, which started on the western side of the range in late Pliocene time is called the *canyon stage*. Unlike the others, it is also represented on the eastern side, but there the gorges have been slashed into the great fault scarp, most of which was formed after the first glacial stage of the Pleistocene epoch. Remnants of the older landscapes are not present on the eastern side of the Sierra Nevada except in a few places where they have been preserved on step-fault blocks. On the eastern side the landscape is mostly a succession of deep gorges separated by narrow crested ridges.

GLACIATION

Except for the great fault scarp on the east side of the Sierra Nevada and Tahoe basin with its beautiful lake, the most startling features of the range are those which have been modeled in part at least by glacial ice, snow avalanches, and frost wedging with associated fall of blocks of rock.

To understand the extraordinary work of ice in sculpturing the high Sierra Nevada requires a brief discussion of the last chapter of earth history, the Pleistocene epoch of Tertiary time or, as it is commonly called, the Glacial epoch.

During the last great marine period of earth history, the Cretaceous, extensive seas prevailed, and the climate over most parts of the earth

was much more equable than today—a characteristic of the important marine intervals. Such climate continued over somewhat reduced areas and with some modifications for the next 15 or 20 million years; but, as the continents gradually enlarged, far-reaching climatic changes set in. Climatic zones were more sharply defined and there was an increasing differentiation of climatic types. While intermediate latitudes were becoming cooler and drier, tropical and subtropical regions which earlier had been so widespread were becoming confined to a relatively narrow belt north and south of the equator. In the extreme north and south and at high altitudes, cold blanketed larger and larger areas. In this progressive climatic change the rise of the continents to abnormal heights above sea level and the extensive building of mountains which had characterized late geological time played an important role. Other factors, not yet determined, were also undoubtedly involved.

When the Glacial epoch started a million or two years ago, the area over which polar climates prevailed rapidly expanded in high and moderately high latitudes both north and south of the equator and at high altitudes. Where the climate was *glacial*, the cold was so intense that a lasting cover of snow and ice began to grow, since all of the snow accumulated during the colder months could not be dissipated during the slightly warmer days and weeks. This blanket gradually increased in thickness, and from the margins of the larger masses, moving fronts or tongues of ice called *glaciers* were projected. Beyond the glacial areas and regions were stretches of the slightly less hostile *tundra* climate where snow and ice melted during a few warmer weeks of the year, and frozen ground was thawed to depths of a very few feet. Below this shallow melt-zone, ice extended for scores or even hundreds of feet, particularly in the higher latitudes of the northern hemisphere and there even today tundra regions are very extensive. Under the permanent ice, water also was frozen in the rocks and remained so throughout the year.

During the Glacial epoch, the climate fluctuated notably over much of the world. Four times the glacial areas expanded, increasing the extent of the lasting mantle of snow and ice until the maximum coverage amounted to about 32 percent of the land above sea level. These four episodes are the *glacial stages*, in the last one of which we live. Then, for reasons as little known as are the causes of their expansion, the areas dominated by polar climate shrank, glaciers and other masses of ice receded or disappeared, and warmer conditions developed over most of the land previously held in the grip of the ice. The magnitude of ice recession during these *interglacial stages* is not known, but doubtless it was different in each as also was the magnitude of advance during the four glacial stages. It is quite probable that, at least during the longest (the second) of the interglacial stages,

practically all of the ice disappeared from the earth. Areas outside of the polar regions were strikingly changed climatically during both glacial and interglacial times.

The length of the Glacial epoch has been extensively debated by many authorities, but evidence so far accumulated does not permit an accurate estimate, the range of opinion being from 1 to 5 million years. Probably the beginning of the epoch was not more than 2 million years back. The lengths of the glacial and interglacial stages also are uncertain. Assuming that the epoch started about 1 million years ago, the following chronology has been suggested:

First glacial stage -----	1,000,000-900,000 years
First interglacial stage -----	900,000-700,000 years
Second glacial stage -----	700,000-600,000 years
Second interglacial stage -----	600,000-325,000 years
Third glacial stage -----	325,000-225,000 years
Third interglacial stage -----	225,000-100,000 years
Fourth glacial stage -----	100,000 years to present
a. Culmination -----	55,000 years
b. Beginning of last principal ice retreat -----	25,000 years



FIG. 11. The young canyon of the Feather River has been deeply eroded into the Sierran bedrock as the result of invigoration of streams caused by the late Pliocene early Pleistocene elevation of the region. The form of this canyon is typical of the non-glaciated portions of all canyons in the range. *Photo courtesy of Western Pacific Railroad.*

If the Glacial epoch includes more than 1 million years, the figures given above must be proportionately increased; further studies also may revise the proportions between glacial and interglacial stages.

Two facts, however, are well established. The glacial stages are the outstanding features of the epoch, but the interglacial stages were of considerably greater length.

Considering the small amount of ice on the earth in pre-Glacial and interglacial time, the creation of the glaciers and other ice masses was rapid and on an enormous scale. As previously noted, the maximum coverage included at least 32 percent of the land above sea level, and in addition vast areas of the ocean were frozen to depths of a few feet or, in some places, as much as a few hundred feet. The last glacial stage, the one in which we live, witnessed the overwhelming of about 27 percent of the land, and of this area more than a third still lies beneath the snow-ice blanket. It is clear therefore that the present is a brief interval in the waning of a glacial stage, a fact not only evidenced by the extent and volume of snow and ice but also by the great areas over which climates still prevail which are not very far removed from the glacial and which could become glacial with a slight decrease in average temperature.

The formation of snow and ice fields which last for long periods represents storage on the earth of water evaporated into the atmosphere and later precipitated as snow. The principal evaporating basin is the ocean, though of course a certain amount goes from the waters of the lands. As the ice masses grew during the glacial stages, the volume of the ocean gradually shrank. Sea level was slowly lowered and the land covered by shallow depths of ocean water emerged. It is believed that the maximum fall of the oceans when the ice reached its greatest extent and thickness was between 300 and 400 feet, whereas at the culmination of the last glacial stage it amounted to 250 or 300 feet. This caused a small increase in the size of continents and islands and the joining of some large and many small islands to the continents or to each other. For example, the water between Alaska and Siberia is so shallow that the above-mentioned lowering of the ocean united the two areas. The area of California increased somewhat as the ocean went down, but the continental shelf off the California coast is narrow in most places, hence the increase was not of much moment. The depression now occupied by San Francisco Bay had a very different appearance during the last glacial stage at least because the depth of water in the Golden Gate is about 381 feet and most of the bay is quite shallow. Therefore when the ocean reached its lowest stand, the bay had largely disappeared and was not restored to material size until sea level had risen appreciably thus bringing the development of the present bay down to the last few thousand years.

Four times during the Glacial epoch ocean level fell and four times it rose, though there appears to have been a slight drop in very recent time occasioned by a moderate chilling of earth climate and some increase of ice. A large volume of water is still locked up in the Green-

land and Antarctic sheets and a much smaller amount in other ice masses. Calculations indicate that, if this ice disappeared, sea level would rise between 50 and 100 feet around the earth. This would submerge many exceedingly low areas along continental and island shores and low islands; also, drowning of the land would isolate certain higher areas as islands.

The profound climatic changes which brought on and did away with the glacial stages naturally were felt far beyond the limits to which the ice expanded. In both hemispheres, though more conspicuously in the northern because of its greater land acreage, the belt of eastward moving storms with its cloudiness and precipitation shifted equatorward as the glacial stages advanced toward their climax, spreading over many regions which are semi-desert or desert today and bringing greater precipitation over both lowlands and highlands. In more northerly and southerly lowlands and particularly in adjacent mountains, both rainfall and winter snow increased. Streams multiplied or grew in volume; lakes without outlets expanded, some developing outlets; and great numbers of new lakes appeared. The changes were more notable in the poleward and higher parts of the regions arid today.

It is clear that each maximum spread of greater humidity over the present dry regions coincided with the culmination of each glacial stage. This climate prevailed about 55,000 years ago, when the fourth glaciation reached its height. The present aridity has evolved principally during the last 25,000 years when the ice recession has been most rapid. Today desert climate prevails over about 35 percent of the land above sea level and vast areas are semi-desert.

The very dry parts of western United States present a splendid record of this climatic change. Professor Flint of Yale University has shown that there are 128 closed basins in this region where evidence of 98 former lakes or expansions of existing lakes has been obtained. Only 8 basins have not yielded positive evidence of former lakes and 20 have been insufficiently studied to show whether lakes were present or not. The 98 basins contained 71 lakes, as some flooded more than one basin.

Mono Lake, at the eastern base of the central Sierra Nevada, was much larger and during the third glacial stage attained a depth of nearly 900 feet. Owens Lake at the south end of Owens Valley increased notably in size. In the Mojave Desert section of the Basin-Ranges province there is record of many former lakes, some of goodly dimension. Panamint Valley held a large one, and another, more than 90 miles long and some 600 feet deep, lay in Death Valley, now one of the most arid regions of the world. The evidence of these former lakes and expanded existing lakes includes wave-cut cliffs and associated wave-cut terraces standing at various elevations along the sides of



FIG. 12. Yosemite region from Mt. Spencer. Evolution Basin in foreground, Mt. Huxley to left, Mt. Goddard to right. *Photo by George J. Young.*

the mountains against which waves pounded, together with beach sediments and other deposits laid down in quiet waters.

It is true that, since the culmination of the last glacial stage about 55,000 years ago, the climate of the earth has become warmer and drier and the ice blanket has notably diminished; but there have been fluctuations both in the climate and in the stand of the ice during even this interval. Neither the advance to the climax of a glacial stage nor its recession has continued unbroken. In very recent times there is abundant evidence of one of these fluctuations, for the greatest warmth and dryness of the fourth glacial stage was reached between 6,000 and 4,000 years ago. Since then, also with minor fluctuations, earth climate has become somewhat cooler and moister. Even as late as 500 B.C., the general climate was warmer than today. This warm, relatively dry episode which began to wane so late in human history is termed the Climatic Optimum.

The proof of the climatic change just referred to is both geologic and biologic. For example, in the Sierra Nevada it has been shown that the regional snow line was considerably higher than today, the average summer temperature also was higher, and the summer season was somewhat longer. This means that none of the small valley-head or cirque glaciers are remnants of former valley glaciers, as had long been believed, but are infants conceived during the cooler interval which started about 4,000 years ago. To judge from the speed with which these glaciers are now wasting, it seems impossible that they could have survived the greater warmth of the Climatic Optimum. The extreme youth of these glaciers also is shown by the freshness of the debris composing their moraines and by the fact that the moraines in some instances contain cores of glacier ice. Moraines of older glaciers, those born during the fourth glacial stage, are somewhat weathered and contain no ice cores.

Certain lakes, like Owens in California, do not contain as much salt as they should if they were residues of larger lakes evaporated to their present size. Therefore it is believed that these lakes disappeared during the climatic optimum and have been recreated in the last 4,000 years. It is possible that most or all existing lakes in western North America may have had similar histories, but this has yet to be proved.

Since the present Sierra Nevada began to rise only a little before the beginning of the Glacial epoch, it soon felt the effect of the increasing cold. The climate became more wintry and the higher parts of the range were blanketed by snow and ice which did not disappear during the slightly warmer months. As the glacial stages advanced, the snow-ice piles became thicker and thicker until they generated glaciers, most of which moved down canyons already scored deep into the rocks by rivers. However, on the western side, the rolling uplands between the canyons provided sites for the generation of small and not particularly

thick ice caps, most of which sent tongues into the canyons, adding to the glaciers already descending from cirques being eroded into the canyon heads. On the eastern side, where the snowfall was less, the valley glaciers were thinner and shorter and there was no room for ice-cap formation. However, tongues from certain caps on the western side found their way into the eastern canyons, as for example, in the Tioga Pass section above Mono Lake.

In the relatively low, northern section of the Sierra Nevada, where the high peaks do not much exceed 6,000 and 7,000 feet above sea level, only cirque or valley-head glaciers and short valley glaciers were present. Since this portion of the range has received little geological study, ice effects are not well known. South of the Kern River where again the peaks are lower as they approach the terminus of the range at Tehachapi Pass, there was little or no glacial ice. The long section between these two parts, however, is quite different.

Around Donner Pass, which is crossed by Highway 40, glaciers of the last stage measured 10 to 15 miles in length and apparently joined to form an ice field approximately 250 square miles in area. Donner Pass was overwhelmed by ice during each of the four stages, long tongues projecting both to the east and west.

Toward the southern end of Lake Tahoe, where the peaks on the western side are 9,000 to 10,000 feet high, the later glaciers on the west side of the main crest were at least 20 miles long, the earlier ones shorter, measuring only 5 to 10 miles. So bulky was the ice mass that part of it was forced across the divide and this together with short valley glaciers developing on the eastern side descended into Lake Tahoe. Between Lake Tahoe and Yosemite National Park, the crests rise from 11,000 to 13,000 feet above sea level. So much snow fell in this section that, on the rolling uplands—remnants of the elevated ancient landscapes—a domed ice cap formed which ran along the trend of the range for about 80 miles and had a width of about 40 miles. Above this considerable ice mass only the highest peaks projected as lonely *nunataks*. From the cap, tongues flowed into canyons already eroded by rivers, and its volume was great enough to force some ice upward through low passes onto the eastern side of the Sierra Nevada. The largest glacier invaded Tuolumne Canyon and in the earlier glacier stages had a length of about 60 miles. The lesser ice of the last stage did not descend the canyon more than 46 miles.

The Yosemite glaciers were the shortest of the tongues in the section under discussion, for most of the ice formed in a relatively small basin and there was only a modest contribution from the ice cap.

Another considerable ice mass about 50 miles long and 30 miles wide developed in the broad basin of the upper San Joaquin River and there were adjacent masses in the basins of Dinkey Creek and the North Fork of the Kings River. The main body was not a cap like



FIG. 13. Cirque glacier on Mt. Maclure in the Sierra Nevada. Photo by G. K. Gilbert, courtesy U. S. Geological Survey.

that in the Yosemite-Tahoe region, for it appears to have been formed by the union of several valley glaciers too thick to be contained in the canyons where they originated. In the last glacial stage, there was not enough ice to create such a field and the glaciers were held within their canyons. The principal ice tongues in this area followed the Middle and South Forks of the San Joaquin River, starting from Evolution Basin and joining into a short trunk stream at Balloon Dome.

In the Kings River drainage area, the canyons were so deep that the ice was held in them. The Middle and South Fork glaciers were the chief ones but the supply was insufficient to cause them to join so they remained separate streams.

In Kaweah Basin, each tributary canyon harbored a vigorous glacier 5 to 7 miles long. The main mass of ice in this region, however, lay in a section extending from Tokopah Valley to the head of the Marble Fork of Kaweah River.

The southernmost of the Sierran valley glaciers lay in the Kern River canyon. During the earlier glacial stages, the ice overflowed the canyon onto the surrounding bench lands which are parts of old valleys generated before the last elevation of the range. The glaciers of the last stage seem to have been confined to the Kern Canyon and its tributaries. The earlier ice was about 32 miles long, extending down to the vicinity of Hockett Peak; the last ice was about 7 miles shorter.

Hockett Peak appears to mark the southern limit of glaciation in the Sierra Nevada.

Today, there are about 60 tiny glaciers in the high Sierra, the best known being two on Mount Lyell, a third on Mount McClure, and a fourth, the Palisade glacier farther south at the head of Big Pine Creek. All are true glaciers, though they are now shrinking, and, because of their small size, they move very slowly. They are not remnants of earlier valley glaciers belonging to the culmination of the fourth glacial stage, but have been created during the slight upswing of the cold, known as the "little ice age." From evidence at hand, it appears that these miniature glaciers began to evolve about 4,000 years ago. Most of them lie in high peak cirques * facing north and northeast though some are on the north and northeast slopes of narrow, comb ridges. In all cases, they are located where abundant snow is drifted by the wind and where they are protected from the sun by the great rock walls above.

The upper part of the Merced River canyon in the Yosemite region was invaded by ice at least three times during the Glacial epoch. The Yosemite glaciers were formed by two principal tributaries, one descending Little Merced canyon south of Half Dome and Liberty Cap while the other followed Tenaya Canyon on the north side. The two streams joined about where Camp Curry and the Ahwahnee Hotel are now located and proceeded down the main canyon. The first two glaciers were much thicker and longer than the third; little evidence remains of the initial stream but the second and third left a fine record. The Merced River canyon prior to the appearance of the ice probably was 1,200 to 1,500 feet deep and possessed the usual V-shaped contour of such gorges. When the glaciers reached their maximum, they filled the canyon which was being appreciably deepened and widened by

* A cirque is a steep-walled, round-bottomed amphitheater evolved by glaciation of the head of a mountain canyon.

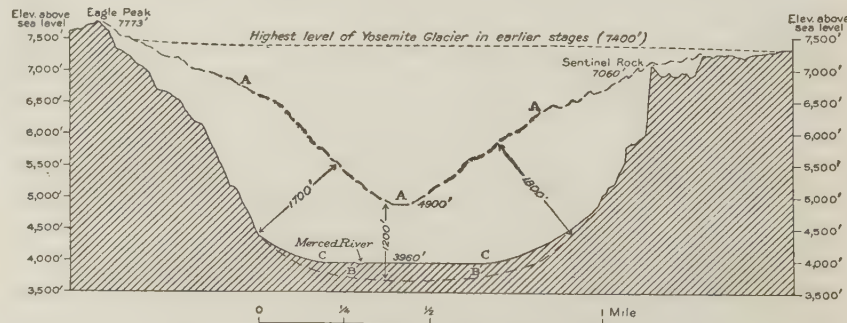


FIG. 14. Dotted line shows probable cross section of Yosemite Valley before glaciation. Solid line shows the present cross-section and figures indicate amount of widening and deepening by the glaciers. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 86.

their erosive action. The modifications cannot be correctly apportioned to the various ice tongues, but in total the canyon was deepened about 1,500 feet at its head where it was widened 1,800 feet on the north side and 1,700 feet on the south side. Excavation decreased in amount downstream. Glacier Point along the rim at the upper end of Yosemite Valley was covered by about 700 feet of ice, but Sentinel Dome which stands a mile back from the rim, the upper 700 feet of Half Dome, the top of El Capitan, and Eagle Peak, highest of the Three Brothers, were not overwhelmed. The lower limit of the ice projected perhaps 5 miles below El Portal where the typical glacial U-shaped canyon begins; the lower few miles of the glaciers were thin and did not erode that part of the canyon to any extent.

The last glacier was much thinner, measuring about 2,700 feet at the head of Yosemite Valley, instead of more than 4,000 feet as did the third glacier, and extended only a short distance below the great, bold promontory, El Capitan. This tongue of the fourth stage left a terminal and a number of recessional moraines as its fluctuated after its maximum advance. *Recessional moraines* are ridges of debris comparable with a terminal moraine and roughly paralleling it. They are developed by temporary advances of the ice after recession from the maximum development has begun. One of the recessional moraines lies a little below El Capitan and now appears as a high embankment well covered with trees and shrubs. It contains great numbers of granitoid boulders embedded in finer debris. As the glacier receded

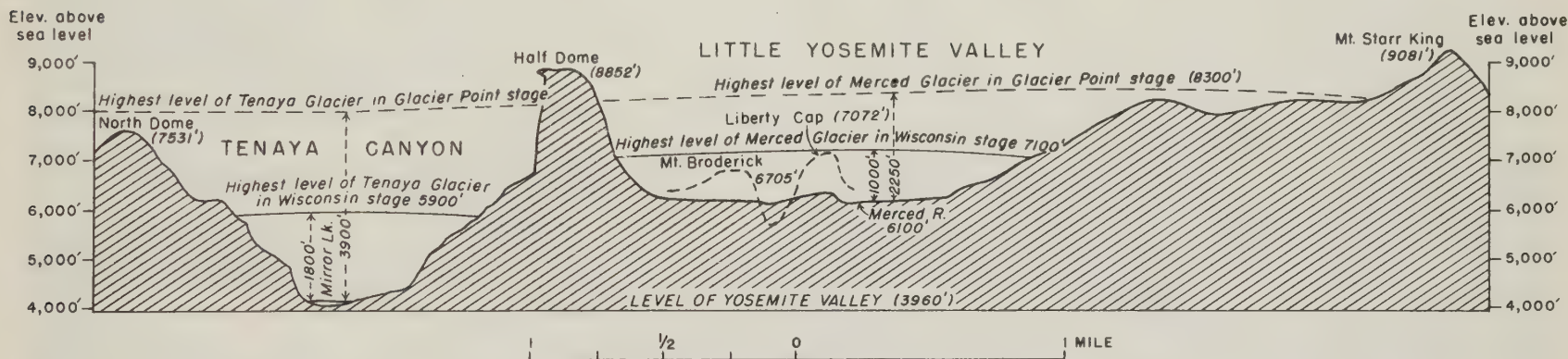


FIG. 15. Section across Tenaya and Little Yosemite Canyons showing highest levels reached by glaciers in the second (Glacier Point) and third (Wisconsin) stages. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 83.

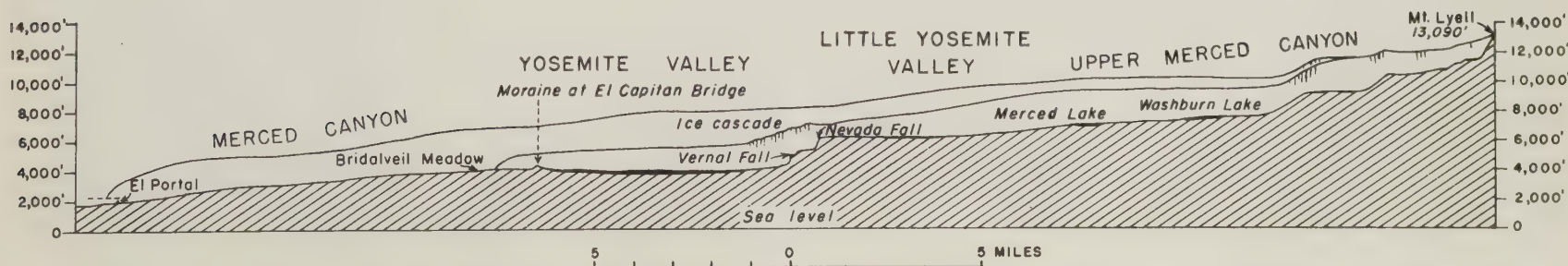


FIG. 16. Longitudinal profile of the two last glaciers that occupied Yosemite Valley and its tributaries during the glacial epoch. The lower solid line shows the last glacier, the upper solid line indicates the much thicker and longer tongue of the ice of the third glacial stage. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 80.

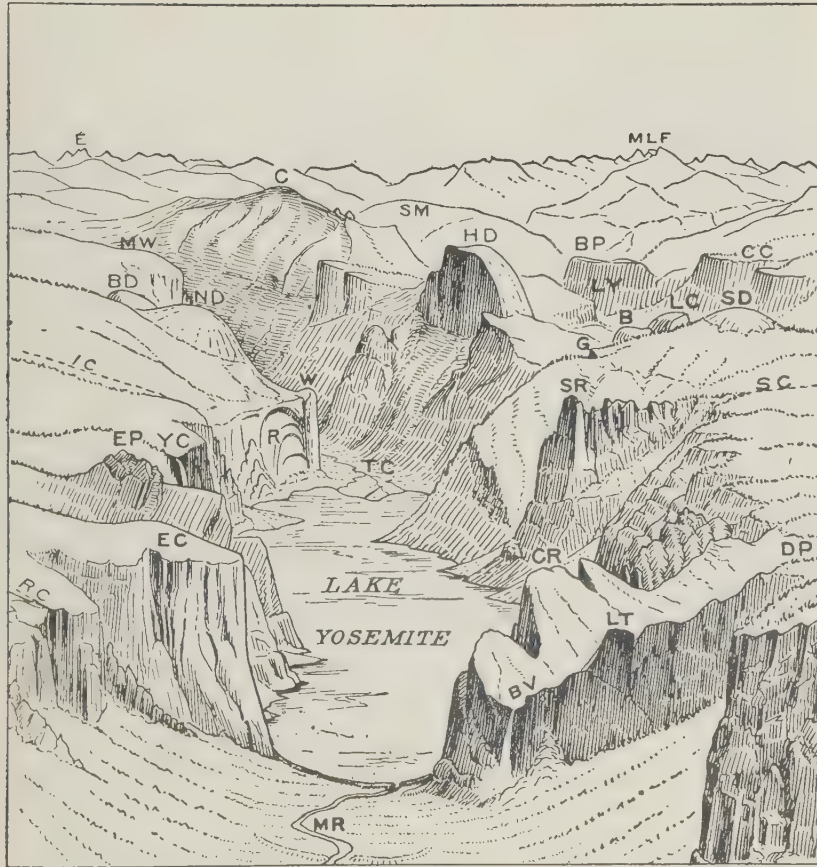


FIG. 17. Bird's-eye view of the Yosemite Valley as it probably was immediately after the ice age. The valley had been broadened and deepened to essentially its present proportions. The deepening accomplished by the ice ranged from 600 feet at the lower end to 1,500 feet at the upper end. A lake $5\frac{1}{2}$ miles long occupied a basin gouged into the rock floor of the valley and dammed in addition by a glacial moraine. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 49.

up the valley from this moraine, a short, wide lake formed between the ice front and the rock barrier. With continued withdrawal of the ice, the lake grew until it extended to the upper end of Yosemite Valley, then attaining a length of about 6 miles. Because of the greater amount of glacial erosion toward the head of the valley than farther down, a basin had been formed sloping in that direction from the lower section where erosion had been much less vigorous. The moraine therefore merely increased the depth of the basin and the lake was much deeper at its upper end than its lower end, measuring perhaps 300 feet. When the lake reached its greatest size, upper Yosemite Valley must have been a glorious sight with the great, deep blue body

of water fringed by gray walls rising nearly vertically above it. But Lake Yosemite did not last long in terms of geological time for into it quantities of sediment were poured by streams coming from the waning ice; thus the basin was filled rather rapidly. At the upper end the *delta*, as such deposits are known, finally rose slightly above average water level, forming at first a small *delta plain*. This advanced down the lake until it reached the crest of the dam, driving out the last of the water. The tributary streams formed the post-glacial Merced River which developed a serpentine path over the even surface of the delta plain until it came to the morainal dam down which it plunged into the unfilled, lower section of the canyon. Thus, though the lower part of Yosemite Valley as far as El Portal is a characteristic, trough-shaped, glacial canyon, the upper part has a flat floor, covered with trees and other vegetation. Since the disappearance of the lake, the Merced River for some unknown reason seems to have rather suddenly developed a shallow breach in the dam, cut a trench about 15 feet deep into the sediments, and then proceeded to widen its valley into a flat floor over which the river lazily meanders.

Little Yosemite Valley, which was evacuated by the ice considerably later than the main Yosemite, had a rock-basin lake about $2\frac{1}{2}$ miles long and a mile wide. Since the basin does not appear to have been more than 50 feet deep, it was filled even before Lake Yosemite.

Mirror Lake in the mouth of Tenaya Canyon is not a glacial product but was impounded by landslides, particularly from a place on the west wall of the canyon behind the Washington Column. This lake is being rapidly filled with sediment, though steps are now being taken to prevent its destruction.

In no other Sierran canyon is there a lake history which matches that of upper Yosemite Valley. Small lakes, chiefly of the rock-basin type, are present and many have been filled, or nearly so, developing little meadows, but no large lake is known to have existed.

The deepening and widening of the valley together with the trimming off of spur ends between tributary gorges have given the bold, barren sides which stand so prominently above the valley floor. The excavation was greatly facilitated or hindered by the abundance or scarcity of joints, for where they were closely spaced removal by quarrying was easy, but where widely separated it was relatively ineffective and wear was accomplished by abrasion. The widest part of the valley, the upper half, therefore lies in closely jointed rock, but the lower part and the tributary gorges are in rock jointed less prominently. In the main valley, the widening decreases from about 1,800 feet on either side to a minimum of 500 feet on either side not far below El Capitan.

Ascent of the Yosemite, Tenaya, and Upper Merced canyons is accomplished by a series of steps, another characteristic of glaciated



FIG. 18. Present configuration of Yosemite Valley. Merced River now meanders through the filled-in bed of Lake Yosemite. *Photo courtesy U. S. Army Air Corps*



FIG. 19. Yosemite Valley from Wawona road. To the left is El Capitan, to the right Cathedral Rock and Bridalveil Fall.
Photo by J. T. Boysen, courtesy U. S. Geological Survey.



FIG. 20. View up Little Yosemite Valley. *Photo courtesy U. S. Army Air Corps.*



FIG. 21. Lost Arrow, Yosemite Valley. Photo courtesy George J. Young.



FIG. 22. El Capitan, Yosemite Valley. *Photo courtesy Ansel Adams.*



FIG. 23. Upper drop of Yosemite Falls (about 1,430 feet), as seen from Merced River. *Norman E. A. Hinds, GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

canyons. The risers of the steps have been evolved in rock cut both by vertical and nearly horizontal joints where quarrying was easy; the edges of the steps and the treads between them are in relatively unbroken rock, which resisted this type of erosion. Each tread is essentially a basin, and the edges are barriers of virtually unquarryable rock, smoothed on the upstream side by abrasion and steepened on the downstream side by removal where more abundant jointing begins. Excavation took place most actively at the head of each tread for there the ice exerted its greatest force because of its plunge downward from the step above.

Thus is explained the replacement of the steeply rising irregular preglacial canyon bottom by a nearly level, basined rock floor, and also why the excavation by the ice was nearly three times as great at the upper end of Yosemite Valley as at the lower. The ice entered the

valley not only by the great stairway from whose steps Vernal and Nevada Falls now plunge, and from Tenaya Canyon, but also by a gigantic cataract from a cap of moderate size on the rolling upland at the base of Half Dome. The deep, walled-in heads of Little Yosemite and Tenaya canyons also were excavated by similar ice cataracts coming from the sheet ice on the upland.

Joints determined the level of each step in the valley. The high stand of the Little Yosemite above the main canyon resulted from the height of a very massive body of granite that forms the upper step of the great stairway in that canyon. The absence of such a step at the mouth of Tenaya canyon is explained by the presence there of jointed rock which greatly aided glacial excavation.

Evolution of the minor features of the walls of Yosemite Valley also have been controlled by the jointing which has played a most significant part in the weathering that has taken place.

Vertical master joints have controlled the position and profile of most of the great cliff faces, including the sheer precipices over which the falls plunge. The smooth, sheer front of Sentinel Rock is bounded by such a joint. Where there is little fracturing, the relief features are massive, as for example the great promontory, El Capitan, which rises so boldly for 3,000 feet above the valley floor. Cathedral Rocks



FIG. 24. Glacial striae in rocks along middle fork of Kings River south of Grouse Meadow. *Photo by George J. Young.*



FIG. 25. Royal Arches, Washington Column (right) and North Dome (upper center). Photo by F. E. Matthes, courtesy U. S. Geological Survey.

also have been sculptured into some of the most massive rock in the entire valley. In contrast are frail Cathedral Spires where the jointing is more closely spaced; elsewhere many recesses which have been excavated along narrow, abundantly broken zones. The Royal Arches have been etched into a complexly jointed slanting cliff face about 1,500 feet high. Along highly inclined and curved joints, frost wedging has pried loose blocks bounded by these fractures. The Washington Column standing just east of the arches has been carved out of a less broken mass or rock.

Adding great beauty to Yosemite landscape when water is abundant are the many falls which plunge from *hanging valleys* standing at various elevations above the valley floor. Most waterfalls are broken in their descent by projecting ledges and should properly be called *cascades*; it is primarily in glaciated valleys that this less common, high, free-leaping type of waterfall is present, though some are formed in other environments. The streams responsible for the Yosemite Falls are small and consequently they appear as veils or ribbons of water rather than as massive cataracts, except for those of the Merced which are somewhat heavier. During the dry season the streams decrease in volume, the falls become largely misty clouds, and some disappear.

Bridal Veil is one of the most perfect examples, emerging from the edge of a V-shaped gulch and plunging over a precipice 620 feet high. In the spring and early summer when the snow is melting the torrent is of considerable size, but during the rest of the year it is filmy and veil-like. Directly opposite on the other side of the valley, Ribbon Falls drop 1,612 feet from the edge of the upland; it is the highest of all, but does not make a free descent throughout for it is held in a narrow, sheer-walled recess in the side of the valley. Even

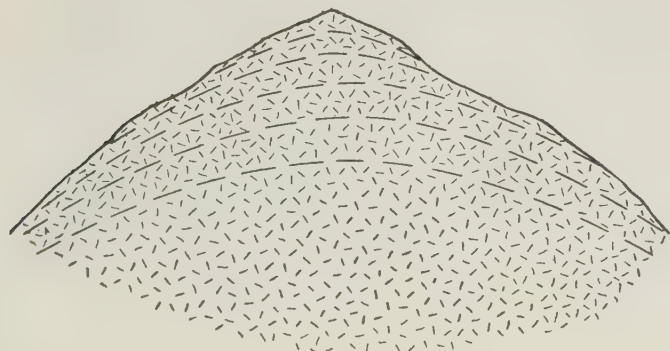


FIG. 26. Diagram showing how, by progressive exfoliation, the original angularities of a rock mass are replaced by smooth curves. After F. E. Matthes, U. S. Geol. Survey Prof. Paper 160, p. 115.

though they are produced by a stream of modest size, Yosemite Falls are the supreme spectacle of the valley. They are in three sections, the upper dropping over a cliff 1,430 feet high and being one of the highest if not the highest free-leaping fall in the world, though it does not clear quite this entire distance in a free plunge. Then the water scatters over several acres, collecting into sheets and rivulets that converge toward a half-bowl of polished granite from which the remade stream races through a narrow winding gorge. After this tortuous descent of 815 feet, the water again plunges over a 320-foot cliff to the floor of the valley.

In the short stretch of the Merced Canyon that connects the Little Yosemite with the main valley, there is an abundance of falling water, for the river descends 2,000 feet in a mile and a half. In the upper part the stream drops over the risers of the giant stairway producing Vernal and Nevada Falls, the former 317 and the latter 594 feet high, and farther down races in a series of raging cascades and rapids.

A rival of Yosemite Falls is the Tueeulala in Hetch Hetchy Valley which has a total drop of about 1,000 feet, but a free leap of only about 600 feet.

Morainal deposits include the terminal and recessional barriers which impounded the lake that lay so lately in the upper part of Yosemite Valley, and side moraines along the valley walls which have been added to by boulder fall and avalanches from the precipitous cliffs after the ice went away.

One of the features characteristic of a glaciated region is polished, scratched or striated, and grooved bedrock, a product of the abrasive action of the moving ice. Particularly in resistant rock like granite, the polish is often remarkable. The scratches apparently are made by sand dragged along by the ice; the grooves, which may reach a yard or more in depth, are formed by resistant boulders grinding into the rock. Such features can be produced in other ways, but, where present over considerable areas and associated with other features of glaciation, can be interpreted only as the product of ice action.

The famous domes of the Yosemite upland have been evolved from giant, joint-bounded columns of granite by long-continued *exfoliation*. This breaking off of shells of rock along more or less concentric fractures apparently has been caused by expansion of the rock as the load upon it has been relieved by erosion. Some of these domes in the Yosemite region were ice covered, others were not. The breaking off of shells of rock has also been aided by the prying action which results when water freezes in the joints. The Half Dome has an exceptional form because its steep northwestern side, a sheer drop of more than 2,000 feet, has been exposed only recently as the result of glacial modifications of the canyon below and the exposure of a nearly vertical



FIG. 27. Northeast side of Half Dome in Yosemite Valley. Frost wedging of joint blocks along a system of curved joints has produced shells that are several feet thick. *Photo by F. C. Calkins, courtesy U. S. Geological Survey.*

system of joints which controls the precipitous face. The form of the southern side is controlled by concentric curved joints along which frost wedging has pried loose shell after shell.

Tahoe Region

In the vicinity of Lake Tahoe, the western mountains range from 8,000 to 10,000 feet in elevation, are broken by deep valleys which have been much ice worn and have prominent cirques at their heads. In the valleys are many rock basins and the characteristic stairway topography already described from the Yosemite section. The mountains in part are narrow ridges but certain areas like the Tallac-Dick's Peak range have broad, flat summits. The higher parts were not covered by ice and consequently have topography characteristic of vigorous mechanical weathering, gravity transfer, and snow avalanching above the limit to which the ice extended. In the mountain canyons there are few morainal deposits. Ice-abraded surfaces prevail, but such features as grooving, striation, and polishing have been extensively destroyed by rock weathering which has followed disappearance of the glaciers. In some places there is considerable burial by talus.

When the ice reached its maximum thickness, it covered all but the highest ridges and flat summits, moving principally from a large area of accumulation in Desolation Valley. Tongues traveled north, east, and south. Other glaciers came from cirque heads of valleys tributary to the main ones. While the main movement was down the valleys, several of the lower divides between them also were covered. This



FIG. 28. Rock basin lakes and Fallen Leaf Lake. Lake Tahoe in the distance occupies the southern part of a long, narrow fault basin. *Photo courtesy Southern Pacific Railroad.*

zone of vigorous glaciation possesses the wildest, most spectacular scenery to be found about Lake Tahoe.

Toward the lake is a zone of morainal ridges and irregular hills in which there are a number of lakes behind morainal barriers. The landscape is far different from that of the mountainous section presenting little that is startling but much that is beautiful. In this zone are Fallen Leaf and Cascade Lakes and Emerald Bay; the upper end of each is a basin scoured out of the bedrock, the lower end of each is made

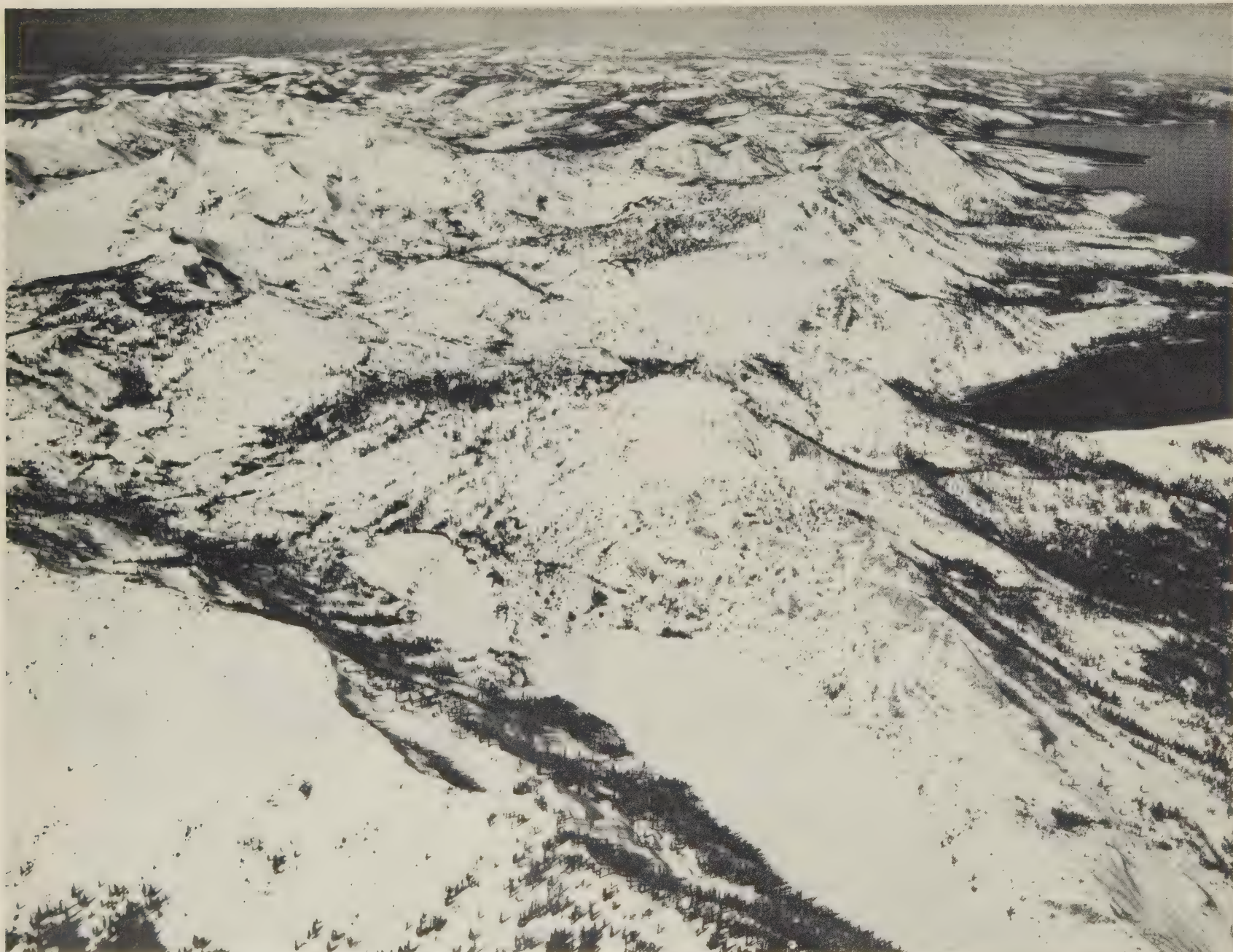


FIG. 29. Echo Lake (foreground) lies in a glacially eroded rock basin. Fallen Leaf Lake (left middle ground) is impounded by a terminal moraine, while Lake Tahoe, the western part of which shows beyond Fallen Leaf Lake, is contained in the lowest part of the Tahoe fault basin. *Photo by U. S. Army Air Corps.*

by a combination of lateral and terminal moraines. At the southern end of the lake plain extending south from Lake Tahoe there is an extensive area of morainal hills and ridges left by a combined piedmont glacial mass formed by tongues moving northward in the upper Truckee Valley and eastward through Echo Lakes basin.

At the southern end of the Tahoe fault basin is a series of flat plains standing at three levels. The most extensive of the three was formed by outwash left by subglacial streams coming from glaciers which lay to the west and south. About 20 feet below this outwash plain is a lower, much less extensive series of terraces eroded by the Upper Truckee River since the ice receded. About 20 feet above the outwash deposit is the third section of the plain; its origin is uncertain but it very possibly represents deposits of the larger Lake Tahoe before its waters developed the outlet eastward by erosion of Truckee River Canyon.

In the heart of the western mountain areas is Desolation Valley, or, as it is called on certain maps, Devil's Basin. On its southwestern border rise the bold slopes of a range dominated by Pyramid Peak (elevation 10,200 feet) which constitutes a barrier between the basin and a group of westward oriented valleys. The Cracked Crags separate Desolation Valley from Glen Alpine and Echo Lakes valleys, and north-directed spurs from the Pyramid Peak Range and Jack's Peak unite at Mosquito Pass and form a divide beyond which is Rockbound Basin. Southward a group of low hills partly isolate Desolation Valley from the steep gorge down which its drainage flows to the South Fork of the American River.

During at least some of the glacial stages, ice so filled Desolation Valley that it overflowed northward into Rockbound Valley, eastward into Glen Alpine and Echo Lakes valleys, and southward into the canyon of the South Fork of the American River. The relatively low elevation of the divides crossed by the glaciers in part has resulted from the heavy wear by the advancing ice.

Largest and most complex of the valleys in this region and perhaps the most attractive scenically is Glen Alpine. In it lies Heather, Susie, Half Moon, and Grass lakes, which occupy rock basins, and Gilmore Lake which is held in by a morainal dam. There are prominent cirques, particularly at the head of Half Moon Valley, and the canyon sides exhibit evidence of vigorous glacial erosion. The rounded rock knobs called *roches moutonnees* are fairly abundant in the valley bottoms.

Echo Lakes valley is similar to, but is not branched like Glen Alpine. Lower Echo Lake is unique in that it occupies a rock basin on the southeastern rim of which is a low morainal ridge. The remainder of the eastern rim is bedrock, from which there is a long, steep, ice-worn slope descending to the lake plain. Down this slope Echo Lakes glacier must have plunged as a gigantic ice cascade.

In the northern part of this mountain section the valleys tributary to Cascade Lake and Emerald Bay show glacial features similar to those in the Desolation area, but they were developed by glaciers which grew in the valley heads.

Rockbound Valley also was deeply eroded by ice flowing in from Desolation Basin.

The longest valley heading in this glaciated mountain region is that of the South Fork of the American River. In the upper part are abundant morainal deposits and associated marshy flats, doubtless fills of small lakes lying between the morainal ridges. This morainal cover extends down the valley about a mile southwest of Phillips, beyond which glacially eroded features are prominent as far as Lovers' Leap, about $3\frac{1}{2}$ miles to the southwest.

Mount Whitney Region

The Mount Whitney region of the Sierra Nevada lies a little south of the middle of the range and is the highest part of the fault block. Mount Whitney, 14,496 feet above sea level, is its culminating summit.

Normally the higher part of a mountain range of great altitude which has been powerfully eroded consists of an alternation of deep, narrow canyons separated by high and narrow crested ridges surmounted by sharp pointed peaks. If such a landscape has been intensely glaciated, the boldness and raggedness of the topography is greatly increased. Mount Whitney and many other peaks in this and other sections of the Sierra Nevada, however, have gently sloping, table-like summits which could not have been formed by initial erosion; rather they are gradually being destroyed by weathering and removal of debris. Therefore these mountains must belong to an earlier cycle of erosion when the landscape looked quite different from that of today. Because of the long time which has elapsed since the first building of the range, 120 to 130 million years, we see none of the landscape developed by the deformation, but we do see relics which have been carved from it. The great folded and faulted ridges brought into being by the compression of the region are gone, but fortunately in places their roots are still preserved showing the structures which were evolved. In the southern two-thirds of the range, erosion has gone deeper into the granitoid batholith which formed in the heart of the mountains as they were originally elevated. None the less, there are scattered remnants of folded and faulted cover which had projected farther than the average into the intrusive mass. After the ancestral Sierra Nevada had been eroded for about 60 million years, it had been so worn down that there remained only rows of hills probably marking the sites of the original deformation ridges; beyond were lowlands sloping gently westward toward the ocean and for an unknown distance to the east. Between the ridges, the streams flowed mostly in northwesterly and southeasterly directions as they had done



FIG. 30. Mount Whitney. Norman F. A. Hinds, *GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

from the early days of the range, with less important drainage directed toward the southwest and northeast.

Possibly 40 or 50 million years ago began the first of a series of uplifts which eventually led to the development of the present Sierra Nevada. The Sierra and the country east of it seems to have been tilted to the southwest so that new master streams flowing in that direction were created. However, lesser streams between the ridges were unable to change direction and continued in their previous courses parallel to the trend of the range. As each uplift occurred all of the streams

were invigorated and cut young canyons deeper into the rocks of the range, the principal ones directed to the southwest, lesser ones to the northwest and southeast.

In the evolution of present Sierran relief the northwesterly-southeasterly crests roughly paralleling the principal crest along the eastern margin are of prime significance. They are among the oldest features of the landscape and are inheritances from the original ridges of the fold-fault range. Some of these longitudinal crests have been carved into folded and faulted rock, as for example the Ritter Range. The south-



FIG. 31. Sierra Nevada, California. Huge talus cones and talus aprons extend far up the walls of the deeply glaciated canyons. Norman E. A. Hinds, *GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

eastward-trending upper canyon of the Middle Fork of the San Joaquin River, paralleling the Ritter Range as far south as Pumice Flat, has been eroded into the same mass of rock and follows the direction of the folds. Le Conte Divide is another example. On the other hand, the South Fork of San Joaquin River has cut its northwestward-trending canyon in the rock of the batholith.

Farther south in the headwaters of the Kings River and in Sequoia National Park, where the folded structures of the Sierra Nevada bend farther south and southeastward, the principal crests and valleys

follow them but are carved mostly in granitoid rock. The Great Western Divide contains folded rocks in the vicinity of Mineral King and in the Kaweah group. The upper Kern River canyon is cut entirely in the batholithic rock; Mount Whitney itself is composed of the same material.

The crest of which Whitney is a part and for which the name Muir has been appropriately suggested, runs south-southeastward for about 17 miles from Shepherd Pass on the north to Cottonwood Pass on the south. It contains seven of eleven peaks in the Sierra Nevada whose



FIG. 32. Mt. Whitney and the Sierra crest. *Norman E. A. Hinds, GEOMORPHOLOGY (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.*

elevations exceed 14,000 feet—Tyndall, Williamson, Barnard, Russell, Whitney, Muir, and Langley—as well as several which are only slightly under that elevation. West of this crest is the upper part of the Kern River canyon. The river's position may have been determined by the ridges on either side, or by a fault, which may be of equal antiquity and which was easier to erode than the unbroken rock on either side.

There are features on the east side of the Muir crest which suggest that another longitudinal valley of great age lay in that direction, a

valley generated long before the late elevation of the Sierran region and the depression of Owens Valley. The crest appears to have been more sharply outlined by valley deepening east and west of it during the episode of elevation, perhaps 40 or 50 million years ago. Many of the peaks in the various crests show a summit platform similar to that of Whitney and some of them slope downward on one or more sides to what evidently were at one time broad valleys. At this time Mount Whitney was a dome-like hill which rose about 1,500 feet above the adjacent valley floors. The distance from the sea coast was



FIG. 33. Franklin Pass. Mineral King is to left of the ridge along the skyline.
Photo by George J. Young.

less than today, for the ocean covered much of the region now occupied by the Coast Ranges and the Great Valley, but the peak must have stood at least 50 miles inland. Comparing this with other regions, it has been concluded that the elevation at the base of the "Whitney Hill" was perhaps 500 feet, so its summit stood approximately 2,000 feet above sea level.

The many flat-topped peaks in the high Sierra similar to Whitney evidently are of the same origin. Perhaps most striking is Table Mountain (13,464 feet) in the Great Western Divide on the opposite side of the Kern River Canyon from Mount Whitney, but there are others in the vicinity. These peaks are about 1,000 feet lower than Whitney, but they are 10 to 15 miles farther west where the general slope of the range carries them to lower elevation. Farther north in the range are Darwin, which has two separated platforms standing at altitudes of 13,841 and 13,701 feet, respectively; Kuna, Koip, and Blacktop in Yosemite National Park which together form a continuous platform about $3\frac{1}{2}$ miles long and between 12,500 and 13,000 feet in elevation. Parker Peak (12,850 feet), Mount Gibbs (12,700 feet), and Mount Dana (13,050 feet) are other examples. The lower elevation of



FIG. 34. Mt. McGee and Evolution Basin. Debris in center was left by glacier.
Photo by George J. Young.

these more northerly peaks is consonant with the slope of the crest of the fault block in that direction from the Mount Whitney region.

Mount Whitney is about 1,000 feet higher than other peaks in the immediate vicinity which have rounded or gently sloping summits, such as Young, Hitchcock, Lone Pine, and Cirque. Mount Langley (14,042 feet) also exceeds by a similar amount summits in its neighborhood. Furthermore the smoothly curving slopes of these lower mountains descend to levels at about 12,000 feet and seem to have been evolved with reference to lower valley floors than either Whitney or Langley, whose slopes descend to remnants of a former valley which now stand nearly 13,000 feet above sea level. Thus it seems that the first elevation of the Sierran region in early Cenozoic time caused the streams to carve canyons about 1,000 feet deep on both sides of the crest of which Whitney and Langley are a part, and of course, similar erosion occurred elsewhere in the range. During the quiet that followed this disturbance the streams passed from youth to maturity, widening their valleys by cutting terraces into the bedrock on either side of their courses. At the same time the mountain slopes were worn back to rather gentle angles. This uplift increased the elevation of



FIG. 35. Part of Evolution group in Sierra Nevada. Mt. Huxley is to right, Mt. Fiske in center, Mt. Haeckel to left. *Photo by George J. Young.*



FIG. 36. The Sierra Nevada in the vicinity of Mount Whitney, California. Before the last elevation of the range, the high peaks were low, rounded mountains rising little over 2,500 feet above wide valleys, a fine example of which shows in the middle ground of the photograph. The canyon of the Kern River has been eroded as the range has risen to its present height. All of the peaks and canyons have been deeply glaciated. A great cirque has been eroded into the eastern side of Mount Whitney, the peak in the foreground; Norman E. A. Hinds, *GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

Mount Whitney to about 4,000 feet, and, because of the valley erosion, caused it to stand another 500 to 600 feet higher above its immediate base. Also, long spurs were carved on both sides of the crest, which are represented by Mount Young (13,493 feet) and Lone Pine Peak (12,951 feet).

West of Cirque Peak and about 1,500 feet below its rounded summit is a gently undulating plateau that extends unbroken for 7 miles to the canyon of the Kern River. This plateau undoubtedly represents part of a broad valley developed by the ancestral Kern River following a second uplift; other remnants are Guyot Flat northwest of Mount



FIG. 37. Trough-like glaciated river canyons, cirques, and snow avalanche sculpture in the high Sierra Nevada near Mount Whitney. *Norman E. A. Hinds, GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

Guyot and Bighorn Plateau between Wallace Creek and Tyndall Creek. Apparently this second deformation, which occurred in late Miocene and early Pliocene time, added about 3,000 feet to the elevation of Mount Whitney, so that it stood 7,000 feet above sea level. Its height above its western base resulting from this further valley cutting was about 2,000 feet as compared with the 500 feet of the "Whitney Hill" first described.

About 1,500 feet below the terrace remnants just described lie broad, gently sloping rock benches that flank the deep Kern River canyon. One

of these is the Chagoopa Plateau which rises from an elevation of about 8,600 feet at the canyon rim to about 10,500 feet at the base of the mountains. These benches are clearly remnants of a former broad valley of the Kern River eroded after a third period of uplift which seems to have added about 2,000 feet to the elevation of the Sierra Nevada, thus raising the summit of Mount Whitney to about 9,000 feet. Probably this was part of the Miocene-Pliocene deformation.

The present Kern River canyon, like other deep canyons in the Sierra Nevada, is the product of vigorous stream erosion accompany-

ing the elevation of the region which started just before the beginning of the Glacial epoch and has continued with notably decreased intensity until the present. The part of the Kern River canyon in the Mount Whitney region is 2,000 to 2,500 feet deep and has been strongly glaciated.

The U-shaped form of the upper part of the Kern River canyon is the product of glacial modification of a normal V-shaped river canyon. There were at least three invasions by the ice and further study may reveal a fourth. Tributary to the master gorge are the canyons of Wallace, Whitney, Rock, and other creeks. Because of the recency of elevation in the Sierran region, these tributaries have eroded gorges only about a mile in length, at the mouths of which water plunges precipitously into the main canyon. Thus they are hanging valleys such as are present in the Yosemite and other sections of the Sierra Nevada. The glaciation of the valley of Whitney Creek differs materially in its various parts. In the lower section, the ice was never more than 600 feet thick and wrought only moderate changes; but, near the base of Mount Whitney, where two tributary glaciers joined, the combined tongue exceeded 1,000 feet in depth and the glacier remained longer than it did far down the valley, altering the original form of the river-cut gorge to greater degree.

On the eastern side of the Muir Crest, vigorous ice attack profoundly modified the canyon heads by eroding large cirques which worked back, destroying pre-glacial slopes and spurs and even carrying away part of the main divide as between Mount Whitney and Whitney Pass, where only the western slope now remains. In some places, as south of Mount Le Conte, the divide was attacked from both sides, and was reduced to a narrow, ragged, comb ridge; in others, as between Mounts Whitney and Russell, the growth of opposing cirques was so extensive as to leave only a thin rock wall. In a few localities, as between Mounts McAdie and Mallory, the divide was destroyed and replaced by a saddle.

Mount Whitney must have been a dome of considerable bulk, even if not of great height above its surroundings, or it would have been reduced to a thin spire like its neighbor, Mount Russell. Even so, the entire eastern half has been cut away by small, but long-lived glaciers which lay upon its slopes until comparatively recent times. Destruction still goes on vigorously because of frost wedging and the fall of multitudes of loosened blocks down the steep slopes. A considerable section of the north side of the peak was removed by the glacial widening of a canyon between it and Mount Russell, and on the west, the lower pre-glacial slope has been destroyed by the enlargement of Whitney Canyon while occupied by ice. The southeast side also lost a small slice by the incision of a narrow cleft, the northernmost of a similar series that break the crestline at intervals of more than a mile

to the south of Mount Whitney and through which occasional views may be obtained to the eastward from the trail up the mountain. These clefts are not glacial features but have resulted from active frost wedging aided by snow sliding along vertical zones where the granite appears to have been sheared by ancient faulting into thin, rather easily removable vertical plates. Only on the southwestern side does Whitney retain its original pre-glacial slope which connects it with the equally unglaciated slope of the main divide.

The upper slopes of Mount Whitney and the entire length of the Muir Crest show no evidence of glacial attack, in striking contrast with the abundant evidence of such action in the upper San Joaquin and Tuolumne drainage areas and in the Kaweah, Kings, and Kern basins. This probably results from the close proximity of the Muir Crest to the southern limit of Sierran glaciation and also to the effect of the Great Western Divide upon which the rising air currents delivered most of their moisture as they do today, thus keeping a greater share from the Muir Crest. Such topographic barriers produce striking climatic contrasts within short distances.

Above the level of the ancient glaciers, the sides of Mount Whitney are furrowed by parallel or converging *snow* or *avalanche chutes* developed by powerful erosion as the great snow cascades swept down the steep slopes. Some of the chutes are 50 to 100 feet deep, and, where close together, are separated by narrow rock ribs which give the cliffs a fluted appearance. The bottoms of the chutes have been worn smoothly concave by the abrasive action of rock carried along by the snow slides. Avalanche chutes are best developed on the west side of Mount Whitney, though they also show well on the north side. Even more perfect, though not so deep, are those on the north side of Mount Hitchcock and in the cirque at the head of Whitney Canyon. The Whitney region is especially rich in this type of sculpture because of rather regular joint and fault structure in the granitoid rock which makes for easy erosion. In other parts, where the joints are more widely spaced or irregular, the chutes are sparse and not well developed.

Studies indicate that snow conditions prevailing on the flattish summit of Mount Whitney are closely related to evolution of the chutes. The avalanches producing them come largely from snow blown to the east as great "snow banners" by terrific winds sweeping across the top of the mountain. Although most of the snow goes eastward, considerable amounts are driven in other directions, accumulating as massive cornices at the edge of platforms, with the snow now and then collapsing to produce the avalanches.

Today in the winter the flat tops of the Sierran peaks are covered only with a thin mantle of snow because of the powerful winds which sweep across them; this condition seems to have prevailed during the

glacial stages. Therefore these summits have escaped the ice attack which has been so effective at lower elevations. Not only this, but there also has been little stream erosion to modify their contour. Heavy showers are rare at such high elevations and snow melts too slowly to produce streams of water. In fact, most of the water sinks into the rocks where it freezes during both summer and winter, cracking the rock to produce the great multitude of blocks which cover the tops of the flat peaks and have fallen down the slopes to form huge *talus cones* and *aprons*.

Thus we have in Mount Whitney and most of the other peaks of the high Sierra, hills and low mountains belonging to a time when the highest stood not more than 2,000 feet above sea level and the Sierra Nevada was anything but an imposing region. This perhaps was 60 million years ago. The changes which have followed have produced the remarkable multiple landscape, of which extensive remnants have been preserved because the vigorous erosion accompanying the late elevation of the range has not had time to destroy them.

Glacial Lakes

In the glaciated sections of the Sierra Nevada are hundreds of small, very beautiful lakes which add immensely to the glory of a landscape undoubtedly almost lakeless prior to invasion by the ice. Although there may have been a good many lakes and swamps when the Sierran region was worn down to its lowest stand 60 million years ago, it is certain that few existed as the mountains rose; the normal processes of mountain erosion are against their formation as the land is too much broken up by active streams. A few basins may be evolved by faulting, landsliding, or volcanic action but their total is far short of the number present in those sections of all mountain ranges remodeled by ice.

The present lakes were produced by the latest glaciers though undoubtedly many were formed as the earlier sheets and tongues left the range. Perhaps in many cases the thinner and weaker glaciers of the last stage merely cleaned out debris-filled basins excavated by the earlier, more powerful ice masses, but without doubt they dug additional basins. In the high Sierra, where the reservoir ice supplying the glaciers evolved in canyon heads and eroded cirques, it etched depressions into the bedrock in which lie hundreds of *cirque lakes*. In this part of the range, and also in the lower northern and southern sections, cirque lakes are most abundant on northeast slopes where the snow was drifted by the prevailing westerly winds and where melting was least effective. The peaks above such lakes are typically unsymmetrical, being steeply cliffed on the northeast side, where the cirques have been incised, and more rounded on the southwest. The rounded slopes are remnants of the ancient hills and low mountains which had been evolved prior to the late elevation of the region.

Cirques not occupied by the last ice have been considerably modified by erosion, their bottoms filled with great masses of talus, and lakes that were present have been converted to meadows. In cirques where the last ice grew, the rock is generally so bare as to indicate that the glaciers have very recently left. Where several cirques are being eroded opposite each other in valleys radiating from a dome-shaped peak like most of those in the pre-glacial Sierra Nevada, the cirque lakes are separated by high ridges commonly having exceedingly ragged crests and the peak itself has been reduced to a steeply sloping spire. On the other hand, if several pre-glacial valleys headed in a group of mountains and converged into a trunk canyon, the cirques have a similar converging pattern, the smaller ones hanging above the canyon. The cirque lakes of such a group therefore are closely associated.

In the Sierra Nevada there are many cirque lakes in basins developed under one of the two conditions described above. In the higher middle section they are present by the hundreds but farther north and south where the glaciation was less intense there are not so many. Gold Lake, at the head of a tributary of the Middle Fork of the Feather River, has a length of about 2 miles and is one of the largest cirque lakes. Somewhat farther south below Sierra Buttes near the North Fork of the Yuba River and around Fall Creek Mountain near the South Fork of the same river, are two groups of lakes. A number of small cirque lakes lie at the headwaters of the Kaweah River in Sequoia National Forest, and fourteen of them, more or less completely converted to marshes, are clustered around the head of the Stanislaus River.

In some of the U-shaped valleys, basins have been excavated below the cirques. The lakes filling them, starting with those in the cirques, are connected by a stream flowing in and out and from a distance look like beads of turquoise or sapphire on a chain. The basins are in places particularly susceptible to erosion where the rock was closely jointed, or where it was slightly less resistant than the immediately adjacent rock. Such chains of lakes are found in the headwaters of Illilouette Creek, 16 miles southeast of Yosemite Valley, between Mammoth Mountain and Mammoth Crest high on the eastern slope of the Sierra Nevada 22 miles south of Mono Lake, and farther south in the Sixty-Lake basin at the headwaters of the Kings River below Mount King.

Garnet Lake and Thousand Island Lake, which have a roundabout drainage to the Middle Fork of the San Joaquin River, stand out among cirque lakes because of the many rocky islands rising above their surfaces.

A few lakes like Silver, Loon, and Pleasant in glaciated branches of the South Fork of the American River appear to lie in the lowest parts of unevenly eroded valley floor. Where the valleys are narrow and steep walled, such lakes are long and oval in plan, being larger

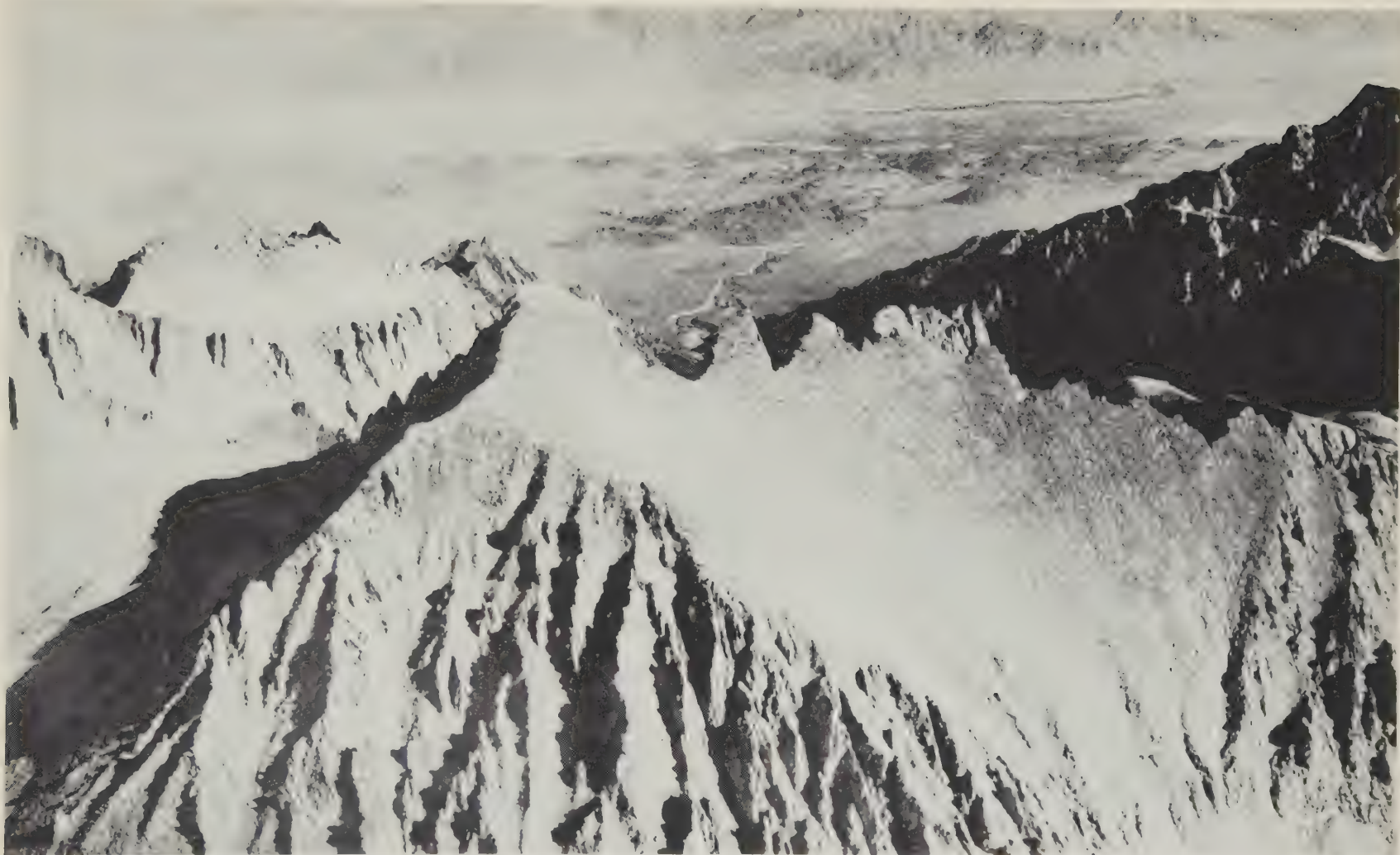


FIG. 38. Prominent snow avalanche sculpturing on the side of a peak in the Mount Whitney region. Where rock structures are favorable the avalanche chutes are separated by narrow, ragged rock ribs like those in the foreground. *Norman E. A. Hinds, GEOMORPHOLOGY (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.*

than the normal rock-basin lakes; but if the glacial trough is wider, the lakes are broader, irregular in outline, and commonly have rocky islets projecting from them.

In the barren, wind-swept, rolling upland toward the higher part of the range, where remnants of the ancient landscape are preserved and where ice caps evolved, small rock-basin lakes, such as in Devil's Basin, a wide area at about 8,200 feet at the head of the South Fork of the American River, also are present. Humphrey Basin, at about

11,000 feet at the head of the South Fork of the San Joaquin River, is another example. In this area is Desolation Lake, about 1 mile in length.

Certain lakes lie at or toward the end of the glaciated section of a canyon and are partly impounded by a barrier of morainal material. The most familiar example is Donner Lake (elevation 6,400 feet) about 3 miles long, on Highway 40 on the east side of Donner Pass. In the same drainage basin, but less often seen because it lies higher in the mountains to the northeast is Independence Lake (elevation



FIG. 39. Donner Lake east of Donner Pass in the Sierra Nevada. The lake has been impounded by a terminal moraine left by a glacier which advanced down the valley shown in the foreground. In the distance are Tahoe fault basin and Carson Range. *Photo courtesy U. S. Army Air Corps.*

7,000 feet), which is 2 miles in length. Well-known Fallen Leaf Lake (about 6,400 feet) on the southwest side of Lake Tahoe is about the same size as Donner Lake and its barrier is a relatively low moraine of the last glacial stage. However, beyond this deposit are huge moraines of the preceding stage; one southeast of Fallen Leaf Lake is about 3 miles long and rises abruptly for 900 feet above its surroundings. Cascade Lake, 3 miles northwest of Fallen Leaf and of about the same size and altitude, lies behind a compound loop of morainal deposits. Twin Lakes, having a combined length of 3 miles, and more than 7,000 feet high on a fork of the Walker River 15 miles southwest of Mono Lake, also lie behind a moraine and have been separated by the growth of delta plain deposits near the middle.

Many of the Sierran lakes have been filled or nearly filled with sediment and now are meadows covered either with small vegetation or trees; these meadows are some of the most delightful spots in the Sierran canyons. The best known is that in Yosemite Valley. Another occupies the lower part of Tenaya Canyon, northern tributary of the Yosemite, and is the fill of a rock-basin lake. Still a third of larger size occupies part of Little Yosemite Canyon. One of the longest filled areas is Tuolumne Meadows which apparently represents the filling of several closely spaced rock-basin lakes.

Most of the meadows are larger than the lakes were, for the deposits generally have spread in some or all directions beyond the margins of the basins.

Numerous lakes impounded by landslides from steep canyon walls are present in the Sierra Nevada. Mirror Lake in Yosemite Valley is one of these. Another is Kern Lake in Kern River canyon.

Artificial Lakes

Many reservoirs have been established in the Sierra Nevada for flood protection, water storage for irrigation and other uses, and power generation. Some of the principal examples are Almanor near the intersection of Highways 36 and 89 at the north end of the Sierra Nevada, a group in the Mokelumne basin which supplies water for cities on the east side of San Francisco Bay and another, principally Hetch Hetchy Reservoir, which is the principal source of San Francisco's water supply. Still other artificial lakes of considerable size are the Pardee Reservoir near Jackson, the Calaveras Reservoir near San Andreas. Near the mouth of the canyon of the San Joaquin River is the Friant Dam which impounds Millerton Lake; this is the second most important element in the great Central Valley Project which is so vital to the Sacramento and San Joaquin Valleys. The principal unit in this project is the huge Shasta Dam in the Klamath Mountains of California. Water is to be exported to various parts of the eastern side of the southern San Joaquin Valley from Millerton Lake to bolster the underground and surface waters which have been severely tapped



FIG. 40. Heather Lake, Alta Peak region, Sierra Nevada. The smoothed rock surface has been produced by glacial abrasion. Photo courtesy U. S. National Park Service.



FIG. 41. Three stages in the filling of Kern Lake in Kern Canyon, Tulare County, by deposition from the inflowing stream. The lake apparently was formed in 1867 by a landslide from the west wall of the canyon which for a time dammed the river. If deposition continues as is probable, a forest-covered lake plain or meadow will be formed. *A*, 1916; *B*, 1918; *C*, 1928. *Photos by T. A. Church.*

by growing population, agriculture, and industry. Many of these reservoirs have become pleasure resorts to which hundreds of people go for outings of various types.

VOLCANISM

Along part of the Kern and Little Kern canyons are the Palisades, part of a lava field that shows at least four distinct flows, each of which possesses rather crudely developed columnar jointing perpendicular to the flow surface. This jointing developed as the lava cooled and contracted. In other places in the field there are more flows, but thin, weathered zones between them makes separation difficult as the lavas are similar in composition. The total thickness of the lava in remnants that are left exceeds 400 feet; how much has been removed by erosion cannot be determined.

In the Toowa Valley below Toowa Range—a high valley drained to the west by a stream known variously as Godel, Trout, Volcano, or Little Whitney creek, and to the east by the South Fork of the Middle Kern River—there is another volcanic field which covers an area about a half mile wide and 4 to 7 miles long. This field contains flows and cinder cones. *Cinder cones* are small volcanoes, generally less than 1,000 feet high, composed entirely of lava fragments. Most of them are built during brief eruptive cycles lasting a few days, weeks, or months.

Toowa Valley is broad and open and stands at an elevation of about 8,600 feet. The cones rise from 400 to 600 feet above the veneer of flows which covers the bedrock. The latest activity blocked drainage, as two prominent cones lie along the axis of the valley—South Fork Cone where Golden Trout Creek enters Toowa Valley, and Groundhog Cone $2\frac{1}{2}$ miles farther east. Two other volcanic centers are in the valley, one at the head of Little Whitney Meadow and one at the Tunnel, north of South Fork Cone. The activity has been so recent that soil is scanty and therefore vegetation is sparse. Several stages in the total eruptive cycle are recorded. It is evident that these eruptions occurred long after the major faults outlining the eastern base of the Sierra Nevada had been evolved.

Earlier basalt apparently of pre-glacial age poured from vents in the canyon of the North Fork of Oak Creek and spread over an alluvial cone formed by the stream issuing from its mouth. Later this lava was partly eroded and covered by debris of the first glacial stage. Basalt flows, probably of the same age, form a number of isolated patches on the south side of Bishop Creek which issues from the Sierra Nevada.

Another considerable volcanic area is located in the headwaters of the Middle Fork of the San Joaquin River to the east of the towering range which has Mount Ritter, Banner Peak, and The Minarets as its principal peaks. The summit of the range is somewhat over 13,000

feet above sea level; Mount Ritter rises abruptly more than a mile above an area of much gentler relief which finally ascends to the lower main eastern divide of the Sierra Nevada, a crest much less imposing than those to the north and south. The rolling area between the two mountainous barriers probably was part of one of the flat valleys belonging to a landscape evolved prior to the last elevation of the Sierra Nevada. The section described has been extensively covered by pumice and lava which is believed to be at least 2,000 feet thick in places. The frothy pumice fragments were exploded from a series of cones at least 30 in number lying mostly east of the Sierra Nevada and extending from Mammoth Mountain to Mono Lake, and including the Mono volcanic range. Most of the pumice came down around the volcanic pipes forming the volcanoes but finer debris was carried far by the wind and is found sprinkling a considerable part of this section of the range. Mammoth Pass and the divide for several miles north are most heavily mantled, and Pumice Flat, as the name indicates, has a goodly cover. Even at Reds Meadow and farther south along the Middle Fork of the San Joaquin River, there is a thin veneer of pumice.

From the alignment of the cones, it is evident that they are located along some of the faults evolved during the great landscape changes in the eastern part of the Sierra Nevada. Certain of these fractures apparently penetrate into the range for some distance as is indicated by the fact that Mammoth Mountain, a greatly worn old volcano, the Little Red Cones on the east side of the Middle Fork, and Pumice Butte north of Fish Creek stand in line with them. The well-known hot spring near Reds Meadow, though somewhat to the west of the line of cones, probably rises along a branch of this fracture system.

Volcanic eruptions occurred along these faults at different times. Mammoth Mountain, a modest eminence which belies its name, was built prior to the beginning of the Glacial epoch and therefore is more than a million years old. So much time has elapsed since activity ceased at this vent that the original form of the cone has been destroyed and there remains only a shapeless mass of volcanic debris. The pumice outbursts are the latest chapter in the recurrent eruptions along the faults, having begun late in the fourth glacial stage and continuing until quite recent time, though not within the historic period.

During the third interglacial stage, more than 100,000 years ago, a fissure opened in Mammoth Pass and from it spilled a flood of basaltic lava most of which streamed into the canyon of the San Joaquin's Middle Fork, spreading out as a tongue from the head of Pumice Flat beyond Rainbow Falls; the flow was at least 6 miles long and is believed to have ranged from 100 to 700 feet in thickness. As the rock cooled after consolidation from the molten liquid, it contracted and joints formed which broke it into rather easily removable columns.



FIG. 42 Eastern base of the Sierra Nevada, separated by a fault depression from one of the westernmost of the fault blocks of the Basin Ranges Province. North of Reno, Nevada. *Photo courtesy Western Pacific Railroad.*



FIG. 43. Feather River Canyon near Rock Dam. *Photo courtesy Western Pacific Railroad.*

When the last glacier descended the Middle Fork canyon, the lava flow formed an obstruction in its path; but the ice was about 1,000 feet thick and therefore overrode the barrier. The prominent jointing made possible easy quarrying by the glacier which was present long enough to remove most of the lava and re-excavate the canyon down to the granitoid rock beneath. Only the most resistant parts of the flow escaped destruction. The largest remnant is a hump in the middle of the canyon which is about 300 yards long and 200 feet high. Because of the resemblance of its tall, straight columns to stacked posts, it has been called the Devil's Postpile, and a National Monument has been created to protect it.

The columns forming the steep western front of the Postpile are high, straight, and very clearly outlined, but those at the southern end are even more remarkable for their curvature and radial arrangement with respect to a center at the top of the pile. On this upper surface may be seen the five- or six-sided ends of the columns, in places still possessing the polish and striations given to them by the over-riding glacier.

REFERENCES

- Atwood, W. W., Jr., Crater Lake and Yosemite through the ages: *National Geographic Magazine*, vol. 71, pp. 326-343, 1937.
- Beatty, M. E., A brief story of the geology of Yosemite Valley: *Nature Notes*, Special Number, National Park Service, 1943.
- Blackwelder, Eliot, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: *Geol. Soc. America Bull.*, vol. 42, pp. 865-891, 1937.
- Blackwelder, Eliot, Supplementary notes on Pleistocene glaciation in the Great Basin: *Wash. Acad. Sci. Jour.*, vol. 24, pp. 217-222, 1934.
- Davis, W. M., The lakes of California: *California Jour. Mines and Geology*, vol. 29, pp. 175-236, 1933.
- Flint, R. F., *Glacial geology and the Pleistocene epoch*, John Wiley and Sons, Inc., 1947.
- Hills, T. M., Glaciation of the upper Kern and its tributaries: *Sierra Club Bull.*, vol. 12, pp. 17-19, 1928.
- Jones, W. D., Glacial land forms in the Sierra Nevada south of Lake Tahoe: *Univ. California Pub. Geog.*, vol. 3, pp. 137-157, 1929.
- Kesseli, J. E., Studies in the Pleistocene glaciation of the Sierra Nevada: *Univ. California Pub. Geog.*, vol. 6, pp. 315-361, 1941.
- Knopf, A., and Kirk, E., A geologic reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California: *U. S. Geol. Survey, Prof. Paper* 110, 1918.
- Lawson, A. C., The geomorphology of the upper Kern Basin, California: *Univ. California Dept. Geology Bull.*, vol. 3, pp. 291-376, 1904.
- Lawson, A. C., The geomorphologic features of the Middle Kern: *Univ. California Dept. Geology Bull.*, vol. 4, pp. 397-409, 1906.
- Louderback, G. D., Lake Tahoe, California-Nevada: *Jour. Geography*, vol. 9, pp. 277-279, 1911.
- Louderback, G. D., Morphologic features of Basin Range displacements in the Great Basin: *Univ. California Dept. Geol. Sci. Bull.*, vol. 16, pp. 1-42, 1926.
- Matthes, F. E., Kings River and Yosemite Valley: *Sierra Club Bull.*, vol. 12, pp. 224-236, 1926.
- Matthes, F. E., Devil's Postpile in the Sierra Nevada and its strange setting: *Sierra Club Bull.*, vol. 15, pp. 1-8, 1930.
- Matthes, F. E., Geologic history of Yosemite Valley: *U. S. Geol. Survey Prof. Paper* 160, 1930.
- Matthes, F. E., Geography and guidebook of the Sierra Nevada; 16th Internat. Geol. Cong., Guidebook 16, pp. 26-40, 1933.
- Matthes, F. E., The Geologic history of Mt. Whitney: *Sierra Club Bull.*, vol. 22, pp. 1-18, 1937.
- Matthes, F. E., Avalanche sculpture in the Sierra Nevada of California: *Internat. Assoc. Hydrology Bull.* 23, pp. 631-637, 1938.
- Matthes, F. E., The incomparable valley, *Univ. California Press*, 160 pp., 1950.
- Matthes, F. E., Sequoia National Park, *Univ. California Press*, 136 pp., 1950.
- Miller, W. J., Geologic sections across the southern Sierra Nevada of California: *Univ. California Dept. Geol. Sci. Bull.*, vol. 20, pp. 331-360, 1931.
- Putnam, W. C., Quaternary geology of the June Lake district, California: *Geol. Soc. America Bull.*, vol. 60, pp. 1281-1302, 1949.
- Reid, J. A., The geomorphogeny of the Sierra Nevada northeast of Lake Tahoe: *Univ. California Dept. Geol. Sci. Bull.*, vol. 6, pp. 89-161, 1911.
- Webb, R. W., Kern Canyon fault, south Sierra Nevada: *Jour. Geology*, vol. 44, pp. 631-638, 1936.
- Webb, R. W., Geomorphology of the middle Kern River basin, southern Sierra Nevada, California: *Geol. Soc. America Bull.*, vol. 57, pp. 355-362, 1946.

BASIN-RANGES

BASIN-RANGES

Margining much of the eastern boundary of California and including a considerable part of the southeastern section of the state is a section of the Basin-Ranges province which consists of north-trending ranges separated either by completely enclosed basins or by troughs open at one or both ends.

In northeastern California, the forces evolving this province invaded the Modoc section of the great Columbia lava plateau; the Warner Mountains, which mark the western boundary of the province in this section are composed entirely of lava. On its western side the Basin-Ranges province abuts against the eastern base of the Sierra Nevada; its southern boundary adjoins the Mojave Desert province.

The portion of the Basin-Ranges province lying in California includes part of the belt folded into mountains by the deformation in Jurassic time. During the Cretaceous and earlier part of the Tertiary, this region, like the Sierra Nevada, underwent long erosion together with certain re-elevations, the details of which are little known at present. In the later part of the Tertiary period, the region was subjected to further deformation, mostly large- and small-scale faulting, though some local folding took place. Along the faults certain blocks were elevated to form a new generation of ranges, while intervening blocks were depressed in similar fashion, developing basins or troughs called *graben*. The result has been the evolution of many discontinuous mountainous areas, most of which are relatively small and not particularly high. Some, like the White-Inyo and Panamint ranges, are much more bulky and tower thousands of feet above the bordering lowlands. None of the blocks approaches the Sierra Nevada in size or maximum elevation.

Throughout the Basin-Ranges province, elevation and depression have been mostly rotational, giving *tilted range* and *graben blocks*, though some *horsts* (vertically elevated blocks) are present. However, many ranges have been so deeply eroded that their original form cannot be determined.

Most of the basin ranges have been examined in reconnaissance fashion, but very few have been studied in detail; more is known about certain of the grabens. So actually there is relatively little information about this vast region, though its general history can be partly outlined.

In general the province is arid, much of it highly so; the dryness increases from north to south and is more intense in lower than in higher basins. Precipitation in Death Valley, one of the lowest spots, averages about 1.4 inches annually. Independence, in southern Owens Valley (3,957 feet) receives 4.83 inches, Bishop at the north end (4,450 feet), 6.05 inches. Over the ranges, particularly the higher

ones, more moisture falls, but there is very little record of this. There is snow on the higher ranges during the colder months, heavy falls on the more northerly and higher ranges, lighter on the lower and more southerly ranges. There also is considerable snow over the northern and higher basins, little or none over those at lower elevation and farther south. The rains are principally summer thunder storms which concentrate over the mountains.

Many of the basins contain lakes; some are permanent, others contain water only part of the year or during intervals separated by more than a year. Most of the lakes are saline or alkaline. On the east and west sides of the Warner Mountains in northeastern California are Goose and Middle Lakes. Mono Lake is at the eastern base of the Sierra Nevada below Tioga Pass. Owens Lake in the southeastern part of the valley of that name formerly was fairly large, but the Los Angeles aqueduct which takes water from the head of Owens River has materially reduced its size and will do the same to Mono Lake. Honey Lake, about 70 miles northeast of Reno, Nevada, and just inside the California border, is dry during the summer.

The Truckee River, flowing from the north end of Lake Tahoe, empties into Pyramid Lake about 35 miles northeast of Reno. Farther south, some streams flowing down the eastern side of the Sierra Nevada empty into Mono Lake. The Owens River, also supplied from the Sierra Nevada, ends in Owens Lake.

Springs emerge at many places in the mountains and basins. Most of the ones in the mountains provide good water, as do some in the basins; but many of the latter have taken up such quantities of salts as their waters have traveled underground that they are anything but potable. Since good springs are of such importance to desert travelers, signs noting their location or the distance to them have been posted at many places, and the government has published various bulletins giving much information about them.

Travel off the main highways in the Basin-Ranges province should not be undertaken without first making careful inquiries about watering places and condition of roads; also proper equipment for a region in general quite hostile, but wonderfully interesting, is essential.

The concept that the ranges and basins of this geomorphic province originated from dislocations along faults was first advanced in 1873 by G. K. Gilbert of the United States Geological Survey. Another member of the same survey, J. E. Spurr, later attempted to account for them as eroded folded mountains since he was unable to find positive evidence of faulting along the margins of many of the ranges. It is recognized that the elevation and depression of the blocks started at different times in different parts of the province and that it con-

tinued longer in some areas than in others. Ranges whose elevation started earlier and ended sooner naturally have changed more than those elevated in very late time or those in which elevation still continues. Along the older ranges evidence of fault control has been largely or wholly wiped out, but in the more recent ones it is clearly defined. Between the two extremes are intermediate stages which can be recognized when the province is studied as a whole. Therefore the absence of clear-cut fault-controlled land forms by no means proves that such were not once present.

The size of the fault blocks varies greatly; low ones that make distinct ridges are only a few miles long and a mile or so wide. The length of the largest blocks is several tens of miles or even more than 100 miles, and their highest peaks rise several thousand feet above the basins. The width of these major ranges may be only a few miles or may reach a few tens of miles.

In the Basin-Ranges province, the fault basins and troughs between the ranges, such as Owens Valley, Panamint Valley, and Death Valley, are narrow compared with the width of the ranges. The boundary fault systems outlining one or both sides of a range can be recognized easily in most places where elevation still goes on or has recently ceased. In older ranges, the fracture systems have been buried by debris from the ranges, which is piled along their bases as *alluvial fans* and *aprons*. These deposits come from streams swollen by flood water, carrying coarse sediment down the canyons through which they flow, and depositing it quickly when their velocity is checked as the water emerges onto the low land at the base of a range. Where several fans unite into a single mass, the deposit is called an alluvial apron.

Along some ranges like the White-Inyo on the east side of Owens Valley, the west side of the Panamint Range on the eastern side of the valley of that name, and the Black Range at the southern end of Death Valley, the fans are small and discontinuous, indicating that vigorous recent uplift has interfered with the accumulation of debris at the canyon mouths. Elsewhere the fans have joined to form alluvial aprons which border more or less the entire mountain fronts. Small knobs or ridges of lower ends of divides between canyons may project through the mantle of unconsolidated debris. The heads of fans forming the great aprons may extend far back into the canyons, in some places to the divides which separate them from those on the other side of the range. Alluvial aprons may eventually join in the middle part of fault troughs or basins with valley-like depressions between them down which flash floods from torrential rains occasionally flow.

One of the best known and most spectacular sections of the Basin-Ranges province in California is that included between the eastern base of the Sierra Nevada and the ranges on the eastern side of Death

Valley, 250 miles away. In this region there are three depressed fault blocks, Owens Valley, Panamint Valley, and Death Valley, which are separated by tilted fault-block ranges. The White-Inyo, Coso, and Argus ranges lie between Owens and Panamint valleys; Panamint and Last Chance mountains separate Panamint Valley from Death Valley; and on the east side of Death Valley are the Grapevine, Funeral, and Black Ranges.

The region exhibits great differences of relief: the elevated blocks have peaks ranging from 8,000 to more than 14,000 feet above sea level, but part of Death Valley is more than 270 feet lower than the level of the ocean. The mountains are newly elevated and therefore rugged; the valleys, on the other hand, have rather even floors.

Owens Valley is a long basin whose floor is between 2 and 8 miles wide; the distance between the crests of the bordering Sierra Nevada and White-Inyo Mountains ranges from 15 miles between Bishop and Bigpine to 40 miles at the north end and 25 miles at Owens Lake near the south end. The floor of the graben slopes gently from an elevation of about 3,600 feet at Owens Lake to about 8,000 feet at the northern extremity of the valley. South of Owens Lake the land rises to a broad, low divide at an elevation of 3,670 feet, which separates Owens Valley from Rose Valley to the south.

The Poverty, Tungsten, and Alabama Hills are isolated low eminences standing above the floor of the valley, but are quite inconspicuous because of the enormous height and bulk of the great bordering ranges. The hills very likely are small, fault-bounded blocks though they may possibly be bedrock remnants left by erosion. Southwest of Bigpine there is a well-preserved volcanic field comprised of explosion cones and lava flows, consisting predominantly of basaltic material, although slightly older rhyolitic rocks, including glassy rocks of various types, are present. Crater Mountain, the highest point in the field, is a cone with crater in the top which rises about 2,000 feet above the floor of Owens Valley.

All evidence points to the subsidence of the Owens Valley block along a series of parallel boundary faults, one at the base of the Sierra Nevada and the other at the base of the Inyo-White Mountains. The graben bedrock in turn is broken by minor faults some paralleling and some lying transverse to the boundary faults. The subsidence of Owens Valley has not been uniform. Partial rotation has occurred and undoubtedly the lesser blocks have moved within the main one. For example the basin holding Owens Lake seems to have been evolved by this uneven sinking and partial rotation of one of the blocks composing the graben.

The rocks composing the Alabama Hills are Triassic or Jurassic volcanics which are intruded by granitoid rock unquestionably of the same age as that of the batholithic complex in the Sierra Nevada—



FIG. 44. View of Owens Valley and the southern end of the Inyo-White Mountains from the Sierra Nevada near Mount Whitney. The low Alabama Hills in the middle ground show remnants of the ancient landscape found in the upper part of the Sierra Nevada around Mount Whitney.

late Jurassic or early Cretaceous. The oldest rocks in the hills are therefore less than 200 million years old. The topography of the Alabama Hills contrasts strongly with that of the nearby Sierran or Inyo-White Mountains fronts, but it is similar to that of the upland around Mount Whitney, where there are well-preserved remnants of landscape far more ancient than that of the great scarps marking the boundaries of the ranges. It is probable that the Alabama Hills are a

fragment of this old landscape separated both from the Sierran upland and from the bedrock under Owens Valley by the great dislocations which have occurred

At the base of the Sierra Nevada, there is an alluvial apron composed of debris brought from the canyons by the mountain streams. The individual fans and the apron as a whole have a considerable slope, 10 to 15 degrees. Because of the steepness of this slope sediment



FIG. 45. The great battered fault scarp of the Sierra Nevada rises about 11,000 feet above the floor of Owens Valley in the vicinity of Lone Pine (foreground). The boundary fault system lies immediately at the base of the range. The Alabama Hills are in the middle ground. At the base of the range is an alluvial apron. Norman E. A. Hinds, *GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

which the streams carry, especially during time of flood, when the most active addition to the fans occurs, is coarse; where the slope flattens abruptly, mostly fine fragments are carried. On the eastern side of the valley, the fans along the White-Inyo Range are isolated from each other and are comparatively small.

Very recent, low fault scarps are present in Owens Valley indicating movement either along the Sierran boundary fault system or

along faults roughly parallel to it. Near Lone Pine several small scarps cut late stream deposits and were evolved by dislocations at the time of the very severe earthquake in 1872 which resulted in much loss of life and damage in the town. Because the scarps are in unconsolidated debris, they have been considerably eroded; in height they range from a few feet to about 25 feet. Recent scarps may be seen west of Bigpine also, one at least being the product of the 1872 disturbance.



FIG. 46. Alluvial apron composed of large and small fans on the eastern side of the Sierra Nevada in arid Owens Valley. *Norman E. A. Hinds, GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

There are many others on the west side of Owens Valley, most of them formed prior to 1872. Like those near Lone Pine, most of these declivities face eastward, but some are directed toward the Sierra Nevada. Horizontal as well as vertical movements are recorded. The total evidence shows that many recent minor dislocations have occurred along a series of roughly parallel faults through a zone 7 or 8 miles wide.

On the eastern side of the valley, recent scarps are not common; one, several feet high developed in 1872, is visible just north of Swansea where it traverses an ancient beach of Owens Lake.

These recent movements are considered evidence of continuation of the settling of the sunken blocks, for similar features have not been recorded within the main mass of the Sierra Nevada.



FIG. 47. Red Mountain, an explosion or cinder cone erupted through a granite hill along a fault parallel to the main boundary fault of the Sierra Nevada. The cone is about 600 feet high. Round about are numerous flows of basalt. This volcanic field lies in Owens Valley.

Between Bigpine and Independence near the eastern base of the Sierra Nevada there is a volcanic field comprised of a considerable number of cinder cones and associated lava flows. Some of the cones are on faults along which there was movement as late as 1872. Crater Mountain, highest of the group, stands about 2,000 feet above the floor of Owens Valley, but this considerable elevation results principally from the fact that the explosions burst through a granite hill

rising nearly 1,400 feet above the valley, hence the cone itself is not particularly imposing.

Most of the cones are on the alluvial apron projecting into Owens Valley from the base of the Sierra Nevada, but some lie along the lower bedrock slope of the range. The most intense volcanic activity occurred between Taboose and Sawmill Creeks where large flows of basalt spread far over the valley floor. The flows are extremely rough,

the surfaces being wild jumbles of clinkery blocks. The lower ends of the flows have been partly covered by later alluvium, but because of inequalities in their surfaces basaltic eminences project through the deposits.

The most perfectly formed cone is Red Mountain which rises about 600 feet above the alluvial apron. An extensive basalt flow poured from the vent, but the crater rim extends unbroken over the head of the flow indicating that the last phase of activity at this center was explosive. The cone is built largely of reddish fragments of lava, hence its name; most of the debris is angular and individual chunks reach an average maximum diameter of about 6 inches, but some bombs which were erupted measured at least 4 feet across. Red Mountain has suffered some erosion and also burial of part of its lower slopes by alluvium, but at first glance it looks as though it were exceedingly recent.

A large but rather imperfectly formed cone stands on the upper end of the alluvial apron between Division and Sawmill Creeks; scattered over its top are many large granite boulders evidently derived from debris of the apron as the eruptions blasted through it.

At an elevation of about 7,000 feet on Sawmill Creek explosive eruptions occurred and basaltic lava flowed from the vent to the mouth of the canyon.

Considerable basalt is present near the base of the Inyo Mountains near Aberdeen on the east side of Owens Valley. Explosions also took place forming a number of imperfect cinder cones, closing the volcanic cycle—one that was probably contemporaneous with that on the west side of the valley.

Red Mountain, previously referred to, stands at the south end of a clearly defined scarp in the alluvium developed at the time of the 1872 earthquake. A short distance to the north along the same scarp there is a minor quantity of exploded debris which did not form a complete cone. Still farther north on the projection of the same fracture is Crater Mountain. Thus three centers of eruption are located along this fault, which evidently is still active.

A large cinder cone west of Fish Springs School was broken by a recent fault along which the displacement amounted to about 50 feet; before it occurred the lower slope of the volcano had been partially buried by alluvium.

On the eastern side of most of Owens Valley is a massive block 110 miles long, with one or two of its highest peaks closely approaching the maximum elevations in the Sierra Nevada. White Mountain Peak stands 14,242 feet above sea level. The range is a continuous mass though there is a depression in the central part culminating in Westgaard Pass (elevation 7,276 feet) which lies east of Bigpine. It is generally known as the White Mountains, though the southern end

may still be referred to as the Inyo Mountains. Although there is no real demarcation between the two parts, in consideration of local preference, the term White-Inyo is used in this description.

On the north, the White-Inyo Mountains terminate quite abruptly at Mount Montgomery; at the southern end there is a broad depression separating them from the Coso Mountains which border the southern part of Owens Valley on the eastern side. The south end of the White-Inyo block therefore is much less clearly defined than the northern. Although the average elevation of the range crest is high, more than 10,000 feet, it is considerably less than that of the corresponding part of the Sierra Nevada on the west side of Owens Valley, hence it is somewhat dwarfed by its greater neighbor.

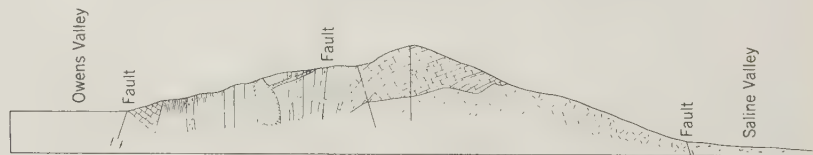


FIG. 48. The Inyo Mountains are a tilted fault block in the Basin-Ranges Province. Rocks in the Inyo Mountains have been intensely folded and are broken by great faults, as shown on the cross-section. A large mass of intrusive granite shows to the west of Saline Valley. *After Knopf and Kirk.*

The west side of the White-Inyo range slopes abruptly to the floor of Owens Valley and is only little less spectacular than the east Sierran front. The western base against Owens Valley is sharply defined, but its eastern margin is much less clear. The northern part of the eastern side is marked by the edge of Fish Lake Valley. Between this graben and Saline Valley farther south, there is an irregular mountainous area not clearly separated from the Inyo Range on the west and the mountains to the east. Saline Valley is an elliptical depression whose floor is about 2,500 feet lower than that of Owens Valley. The eastern face of the Inyo Mountains fronting on this valley is quite as abrupt and majestic as the eastern side of the Sierra Nevada.

The White-Inyo Range is a gigantic fault block, but the evidence of the dislocations producing it is most clearly shown at the two extremities. At the northern end, the inter-canyon spurs projecting into Owens Valley are terminated by remarkably large, clearly defined triangular facets whose sharp edges and geometric perfection make them extraordinarily fine illustrations of this important feature of recently uplifted fault blocks. At the southern end, which is almost completely covered by a thick mass of basaltic lava flows overlying an exceedingly even elevated erosion surface, actual dislocations of the flows are visible. Between the two ends of the range the evidence is less conspicuous, probably because the dislocation has been distributed along parallel fractures and this has prevented the development of prominent triangular facets. Such movements as have occurred in the



FIG. 49. The White-Inyo Mountains on the east side of Owens Valley are a fault-block range considerably smaller than the Sierra Nevada. Evidence of faulting is prominent along the western front of the range. Owens Lake lying in the lowest part of the fault basin between the two ranges shows in the foreground. *Norman E. A. Hinds, GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

middle section appear to have taken place along faults which parallel the boundary fault for a distance and then run into the body of the range.

Other evidence of the fault block origin of the White-Inyo Mountains is the straightness of the western front and its independence of the bedrock, for the front transgresses the trend of the rock layers as is commonly the case in fault block ranges. The eastern front does not provide so straight a base as the western side. However, the topography of the eastern front in many places shows extensive faulting, especially in the great escarpment margining Saline Valley where very prominent triangular facets are present. Further evidence in the same place is the badly crushed rock along this escarpment which could only have been produced during dislocation along a major fault system.

The slopes of the west side of the Argus Range, and the east and west sides of the Coso, Panamint, and Black Ranges are all exceedingly steep, not greatly battered fault scarps. The west sides of the Coso, Argus, and Panamint Ranges also include minor scarps known to have been developed by step-faulting, for in many places traces of these lesser faults can be observed, as well as displacements along them. Highway 190 crosses both the Coso and Panamint Ranges on its way to Death Valley.

Perhaps the most conspicuous fault zone bounds the east side of Panamint Valley and marks the base of the Panamint Range, for the dislocation here has been very great. There are evidences of recent movement, particularly south of Wildrose Canyon where the range front is extremely high and abrupt and the alluvial fans at the mouths of the canyons are feebly developed. For this reason the lowest part of Panamint Valley is near the base of the range rather than near the center of the valley as is normally the case. However, because the volume of debris in the present fans is only a small proportion of the total removed from the Panamint Range in the erosion of the canyons on its western side, Panamint Valley must have sunk as the range was elevated and older fans have been buried by those growing from the eastern side of the Argus Range on the opposite side of Panamint Valley. Even some of the new fans along the Panamint Range have been broken by recent faulting and parts of them elevated. In some places, the bedrock scarp, which rises to a height of 2,000 and 3,000 feet, slopes as much as 35 degrees; apparently it is the continuous footwall of the fault so recently exposed by dislocations. The rock in which the facets are cut is greatly crushed, sheared, and discolored, additional evidence of the presence of the surface of the fault.

One of the most striking bits of evidence favoring the recency of the faulting along the west side of the Panamint Range is a large north-trending graben in the alluvium just south of Wildrose Canyon. This

depression is more than 3 miles long, nearly a mile wide, and 400 feet deep in its deepest part.

Between the Coso and Argus Ranges is a hilly area of low relief which is a somewhat deformed and eroded portion of an old landscape found in the higher parts of the ranges. This section includes Coso Valley and the hills immediately to the east, the Darwin Hills, and also Darwin Wash. Lower Darwin Wash, east of the Darwin Hills, is an alluviated area in which white lake beds indicate the presence of a former water body. Headward erosion of Darwin Canyon, a narrow gorge which empties into Panamint Valley, has recently drained the lake; as a result the base of erosion for most of the intermittent streams draining Darwin Hills and the west slope of the Argus Range has been lowered about 2,000 feet, causing considerable dissection of the lake beds and the alluvium in Darwin Wash.

Remnants of the ancient erosion surface are found elsewhere in the mountain ranges, and are being progressively cut to pieces by headward erosion of canyons which have been cut during the late uplift of the fault blocks. At one time this surface appears to have been very widespread over the region and probably was continuous with remnants found in the Sierra Nevada. In the western part of the section under present discussion, thin flows of basalt spread across the erosional plain completely burying much of it, but, in places, hills several hundred feet high rose above the general level and were partially or completely surrounded but not covered by the flows. The age of this erosion surface which shows in the Sierra Nevada, the Coso, the Argus, and Panamint Ranges at least, is of interest and some information is given by geological features in the Coso Range and in the Mojave Desert farther south which indicates that the surface had been evolved by the late part of the Pliocene or the very early Pleistocene epoch. Remnants of a similar surface have been reported from ranges in southwestern Nevada and possibly from the San Bernardino Mountains of southern California. If all are part of a once continuous landscape, a large area had been reduced to most modest relief when the late faulting occurred.

Death Valley, one of California's most interesting and spectacular scenic areas, is a completely enclosed graben about 130 miles long and from 6 to 14 miles wide. On the western side, Panamint Mountains rise to a highest elevation of more than 11,000 feet; the Last Chance Range to the north is somewhat lower. Along the eastern margin, three ranges, the Grapevine at the north, the Funeral, and the Black at the south complete the enclosure. Each of these is distinctly lower than the Panamint.

Death Valley basin and the bordering ranges owe their origin to such profound fracturing as has been described in areas farther west. The deepest part of Death Valley, lying between the Panamint and

Black Mountains, has been lowered below sea level, though the region as we see it today has not been invaded by the ocean. However, in the past, before development of the present relief, the sea invaded this part of California several times, as is proved by the wealth of marine fossils contained in many rock layers exposed in the ranges.



FIG. 50. The low cliff in the alluvium at the base of the Panamint Range in Death Valley is a fault scarp formed by recent movement along one of the fractures close to the base of the range. *Photo courtesy National Park Service.*

The faulting, which started in the late part of the Pliocene epoch and is still going on, is extremely complex. Its effects show best along the eastern face of the Black Range where the most recent and most active movements have occurred. The lower slope of this range is extremely steep; although it has suffered some erosion, it is one of the best preserved fault scarps in the United States. The road along the east side of Death Valley from Furnace Creek south runs close to the scarp and affords easy access. For 15 miles below Furnace Creek, the boundary fault system cuts across Tertiary rocks, but, farther south, there are precipitous slopes in ancient, resistant formations which roughly outline the surface of the fault. Three miles north of Badwater, the deepest point in the valley (270 feet below sea level), a fault between the Tertiary and the very old rocks is clearly exposed for many thousands of feet where it extends upward into the range, and the fault surface is continuous with the valleyward slope of the ancient rock farther to the south.

Because of the height of the ranges around Death Valley and their consequently steep slopes, a host of valleys has been eroded into them and the streams have carried great quantities of debris into the basin forming alluvial fans and aprons. Along the Black Range, the fans are small and discontinuous and much of the lower part of the range front is abnormally steep, both part of the evidence that this block has been recently elevated to a considerable extent or that the valley has sunk. Elsewhere the fans have united to form aprons having moderately steep slopes from the toe of the deposit to its upper end which may be miles up the canyons. This is notably true along the west front of the Panamint Range where the fan heads extend far back into the mountains. The steep slopes of the fans and the coarse debris composing them testifies to their speedy formation. In places the fans are broken by low scarps, indicating the presence of active faults beneath them. A very good example may be seen about a mile south of Furnace Creek Inn where a scarp lies just east of the highway and extends parallel to it for some distance; another is at the base of the Panamint Range.

The floor of a considerable portion of southern Death Valley is made of rock salt formed by the evaporation of a large lake. As shown previously, during the climaxes of the glacial stages, more snow fell on the California mountains and in most places over the lowlands more rain than does today. At various places around Death Valley, there are wave-cut terraces and deposits as much as 600 feet above the valley floor. These terraces, although faintly outlined, can be distinguished,



FIG. 51. Salt left by evaporation of lake in Death Valley is being dissolved by water falling on the valley floor and by water migrating downward from the adjacent ranges. The water is an exceedingly bitter brine. *Photo by Willard.*



FIG. 52. Sketch of Death Valley from the western side. Death Valley is a long narrow fault basin, part of which has sunk below sea level as the adjacent ranges have risen. At the base of the Panamint Range, on skyline, is a great alluvial apron formed from debris which streams have brought out of the canyons. The rough land in the foreground is weathered salt left when the large lake that formerly filled the basin evaporated. *Photo courtesy R. N. Wheeler.*

as for example at Mormon Point and on Shore Line Butte, which is a hill of black basaltic lava rising above the valley floor, a mile northwest of Ashford Mill. This ancient lake has been given the name of Manly, for one of the early explorers in this region.

Evidences of other lakes which occupied the valley at earlier times has been gained from borings into the sediments. A well 1,000 feet deep along the road across the Devil's Golf Course, passed through alternate beds of clay and salt without reaching bedrock. Each pair of salt and clay layers represents the evaporation of a lake, the salt representing the final product as the water disappeared.

In the middle part of Death Valley, principally north of the road leading to Stovepipe Wells, is a small group of sand dunes made up largely of quartz sand.

Considerably north of the sand dunes and only a few miles from the famous Death Valley Scotty's Castle are the Ubehebe Craters, a group

of small cones built by explosive eruption of fragments of basaltic lava. Probably these cones overlie one of the faults traversing the graben bedrock, and were erupted only a few hundred years ago. The craters in the tops of the cones are well preserved and in their walls the various layers of fragments blown out by the different explosions are well marked. The volcanic cycle seems to have been a brief one, as is normally the case with volcanoes built solely by explosion. In the southern part of Death Valley there has been liberal outpouring of basaltic lava along the faults.

Cenozoic deposits present in the valley are especially notable for their high coloring, as for example along the base of the Black Range south of Furnace Creek Inn, where a striking badland area has been developed by the occasional torrential storms. Because the rocks are quite unprotected by vegetation and surface slopes are steep, the sheet and flash floods are literally ripping the deposit to pieces. A labyrinth

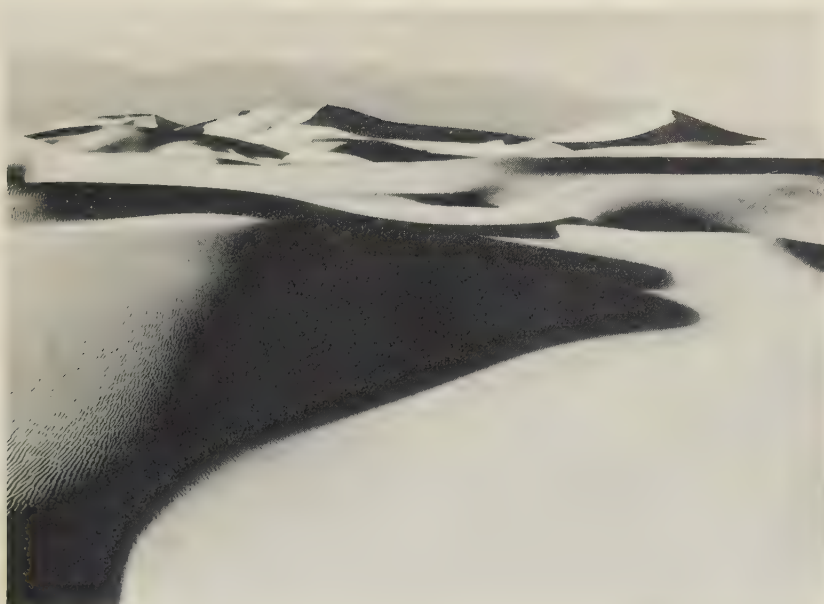


FIG. 53. Sand dunes near Stovepipe Wells in Death Valley. The dunes are composed of loose sand drifted over the area by wind, and piled against obstacles, eventually covering them. *Photo courtesy National Park Service.*

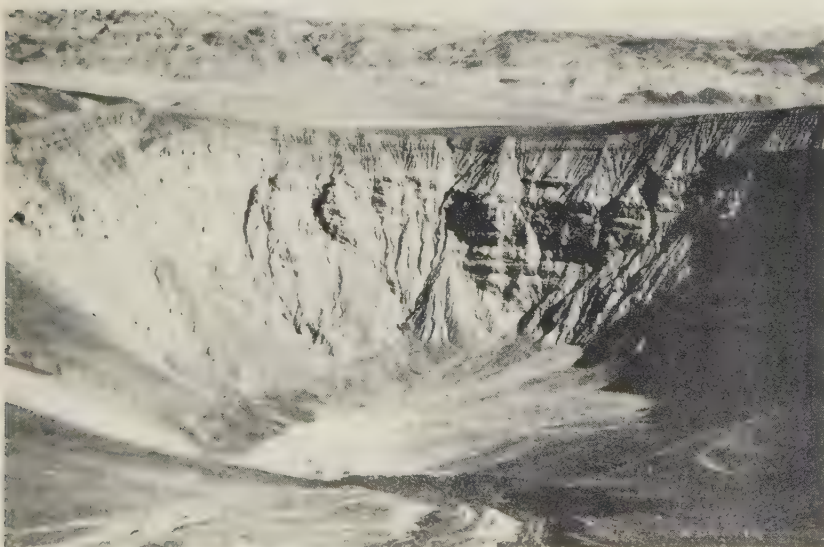


FIG. 54. Ubehebe Craters in the northern part of Death Valley. Layers of lava fragments erupted during each explosion show in the crater walls. *Photo by Willard.*

of deep, narrow gorges lies between high, sharp-crested ridges. Most of the sediments are brilliant yellow in color but there are many other shades.

In the Tertiary deposits are the famous borax minerals mined long ago and transported by the giant wagons drawn by the twenty-mule teams.

Panamint Valley is a narrow fault basin about 60 miles long lying beyond the mountains bordering the west side of Death Valley. About 15 miles from the northern end, alluvial fans built out from the ranges on the two sides have coalesced, dividing the basin into two parts separated by an alluvial ridge. At the southern end, this graben is narrow, less than a mile across near the San Bernardino County line, and not more than 2 miles wide for some distance to the north. The alluvial slopes rise steeply to the mountains on both sides. Farther north, near Ballarat, Panamint Valley widens to about 10 miles and maintains this approximate width for a considerable distance, beyond which it again narrows.

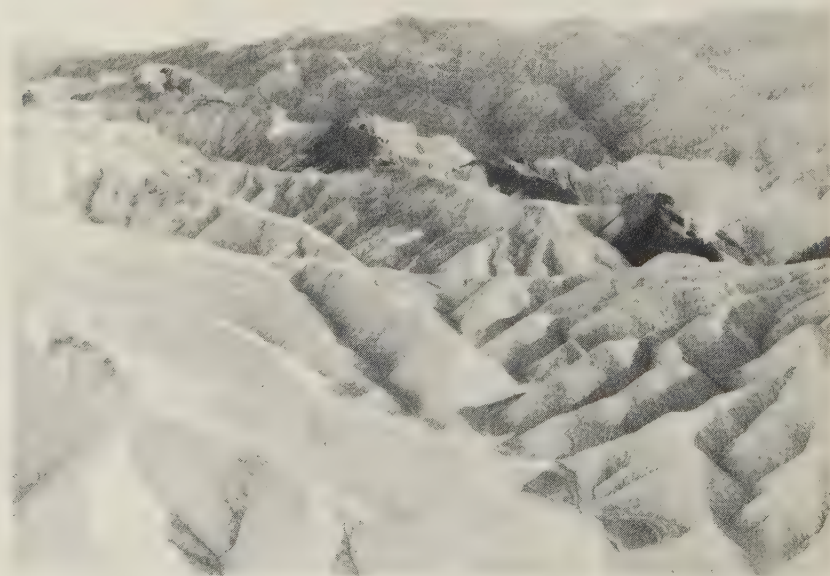


FIG. 55. Badland area south of Furnace Creek in Death Valley National Monument. *Photo courtesy National Park Service.*

At the south, the west border of the valley is the Slate Range which farther north (about latitude 36°) merges with the Argus Mountains. At the southern end the eastern border is formed by Brown Mountain which gives way to Wingate Pass 8 miles northward. This is a low, nearly level valley about 2 miles wide which slopes gently eastward for several miles and then drops rather sharply into Death Valley.

The summit of the pass is less than 300 feet above the Panamint Valley floor, but the mountains to the north and south rise several thousand feet higher. North of Wingate Pass, the eastern side of the valley abuts against the great Panamint Range, whose high point, Telescope Peak, is 11,045 feet above sea level.

The lowest part of Panamint Valley is a *playa* or intermittent lake about 17 miles long and 3 miles wide at its widest part. This flat is nearly a thousand feet lower than the lowest part of the valley at its south end and about 600 feet below the alluvial divide which separates the valley into two parts. During the glacial stages a large lake was present in Panamint Valley. There are wave-cut terraces and deposits of tufa standing several hundred feet above the valley floor. Panamint Lake was contemporaneous with Searles, the greater Owens, and other lakes in the western desert country. Searles Lake at one time apparently overflowed into Panamint Lake and was in part responsible for the notable size and depth of the latter. However, there is a considerable area of mountainous country tributary to Panamint Valley and the increased rainfall and snowfall over these heights during the moister episodes must also have provided sufficient water for a lake of moderate size. The uppermost terraces cut by the waves are not distinct, hence it has not been possible to determine just how high the water rose on the mountain slopes. Tufa has been found at elevations as high as 1,980 feet, which is practically that of the summit of Wingate Pass, and it is possible that for a time water did flow through this break in the mountain barrier into Death Valley. If the maximum depth of Panamint Lake was governed by this overflow area into Death Valley, the depth of water was about 930 feet and the area roughly 272 square miles. Not only was the southern part of Panamint Valley covered, but the water overtopped by about 300 feet the alluvial divide which now isolates the northern from the southern section. This great body of water evidently existed for a considerable time in what is now desert land.

No saline deposits comparable with those of Searles Lake have been found in Panamint Valley, the deposits formed in it being fine clay and sand.

One exceedingly interesting section of the Basin-Ranges is Searles Lake Valley, a rather narrow, elongate depression almost completely enclosed by mountains. The boundary of the northern half is the Slate Range which rises 3,000 to 4,000 feet above Searles Lake and attains a maximum altitude of 5,565 feet above sea level. South of this range, the border of the valley bends to the southwest and is composed of high hills extending as far as Klinker Mountain. These hills are along the Garlock fault and undoubtedly have been evolved by movements along this zone. The western border of the valley as far south as Salt Wells Canyon is formed by the Argus Range, and south of this there is a lower unnamed range.

In Searles Valley there was a large lake or series of lakes during the glacial stages of the Glacial epoch, while today there are only a few inches of water during the rainy season, hence present Searles Lake is an intermittent lake or playa. Evidence of the greater water body is provided chiefly by wave-cut benches on the mountain sides up to 640 feet above the valley floor, at an elevation of 2,262 feet above sea level. When the lake reached its highest level, it extended westward through Salt Wells Valley and covered a large area in Indian Wells Valley. The lake at this time overflowed southeastward also into Pilot Knob Valley and thence into Panamint Valley.

Other evidence of the expanded lake is provided by deposits of the porous lime rock, called *calcareous tufa*, which was precipitated from the waters. In places the tufa merely coated other rock, but in some localities it accumulated to considerable thickness. It is especially well developed at the Pinnacles which are steep-sided knobs rising about 100 feet above their surroundings some 15 miles south of Trona, near where the railroad turns to the southwest. Similar masses also show $1\frac{1}{2}$ miles southwest of Salt Wells, a short distance east of the canyon road to Randsburg.

Unique features associated with ancient Searles Lake are the saline deposits underlying part of the area; they are outstanding both in the purity of the salt beds and also in the variety of minerals composing them. Also, there is an unusually high content of potash, for which the deposits are worked. The salt body extends to depths of 60 to 100 feet in the central part of the playa. Laterally it grades into clay and sand containing less and less salt, which, in turn, pass into the coarser alluvial sediments along the margin of the valley.

When largest, ancient Searles Lake covered an area of about 285 square miles. It was one of a system that existed in Owens Valley and farther south during the moister climates coinciding with the culmination of the glacial stages. Most of the water came from the east side of the Sierra Nevada, forming Owens River, which ran to the lower end of Owens Valley where it was impounded to form a lake much larger than present Owens Lake. The water finally overflowed southward making a stream which ran into Indian Wells Valley where it in turn was backed up behind a low barrier forming a small lake. This overflowed into Salt Wells Valley and thence into Searles Valley. As previously noted, Searles Lake became too high for its barrier, spilling into Panamint Valley where it contributed to a lake that for a time was 930 feet deep. At this stage, Searles Lake water also flowed into Salt Wells and Indian Wells valleys. Over large areas the surface of the Searles playa is characterized by the remarkable *self-rising ground* produced by the formation of salt crystals from water evaporating in the sediment. Alkali crusts are present in places on this ground, increasing in continuity toward the center of the playa.

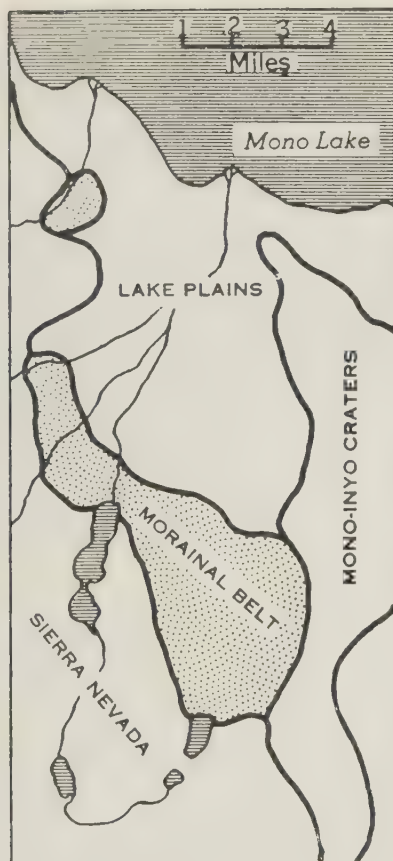


FIG. 56. Map showing principal physical divisions of the district south of Mono Lake on the east side of the Sierra Nevada. After W. C. Putnam.

Mono Basin

One of the most interesting and spectacular parts of California is that in the vicinity of Mono Lake which lies in a fault basin at the base of the east central part of the Sierra Nevada. This area is about 360 miles north of Los Angeles and 180 miles east of San Francisco. It is traversed by Highway 395 from which three roads branch off. One leads across the desert basin to join Highway 6 at Benton Station near the Nevada border; the second ascends the Sierra Nevada through Leevining Canyon reaching the crest of the range at Tioga Pass and then goes down the western slope through Yosemite National Park; the third is a short stretch going past June Lake and back to Highway 395 through Reversed Valley.

The relief of this section is striking, for on the west the great battered fault scarp forming the eastern face of the Sierra Nevada rises more than 6,000 feet above the desert basin. The scarp is broken by deep canyons which are separated by narrow, ragged ridges. In contrast, the relatively flat basin stretches for miles to the east where it abuts sharply against various ranges of the Basin-Ranges province. In this fault basin three divisions may be recognized: Mono Lake and the associated lake plain, the morainal belt, and the Mono-Inyo craters.

The present Mono Lake is fairly large, measuring 14 miles in length by 10 in width, the greater dimension being in the east-west direction. The greatest known depth, recorded in 1889, was 152 feet between Paoha Island and the Mono Craters to the south. The present depth probably is somewhat greater, though the lake level is falling and probably will continue to fall because of withdrawal of water from tributary Rush and Leevining Creeks for the aqueduct supplying the City of Los Angeles. The lake water which contains sufficient concentration of various salts to make its taste unpleasant, has a foul odor.

Clearly defined beyond Mono Lake are old shore lines which show its much greater size and depth during the culmination of at least two glacial stages. In 1947 the surface of the lake stood 6,416 feet above sea level; easily recognized older shore lines stand as much as 654 feet above this elevation and a fainter one, less certainly identified, is about 100 feet higher (between 7,170 and 7,180 feet). When at its largest size, this greater Mono Lake, which is called Russell after the geologist who first worked out its history, was about 900 feet deep. The shoreline at 7,000 feet appears to mark the stand of the lake during the later part of the last glacial stage; the higher, less distinct one belongs to an earlier part of the same stage.

Field evidence indicates that Lake Russell overflowed into Adobe Valley when it reached its greatest size, but not during the last rise. The outlet cut a channel in basalt across the Mono Basin divide at approximate elevation of 8,150 feet, east of the now abandoned Benton-Bodie stage road, and this channel connects with Adobe Valley by a number of linking, shallow basins and finally by a deep, narrow canyon also eroded in basalt. In the eastern part of Adobe Valley there is a chain of lakes which appears to be part of a once-connected drainage system. Adobe Valley is linked with Owens Valley farther south by a narrow channel in the Benton Range, west of Benton, Nevada. Thus it appears that, during the highest rise of Mono Lake waters, Lake Russell was the northern end of a chain that extended through Owens Valley by way of Searles and Panamint lakes to that in Death Valley (Manly) which has already been described.

As the waters of Lake Russell receded to their present position, they left a broad area covered by deposits which had been accumulated on the floor of the lake. This area is called the lake plain, but actually it is a succession of terraces which are clearly defined to an elevation of

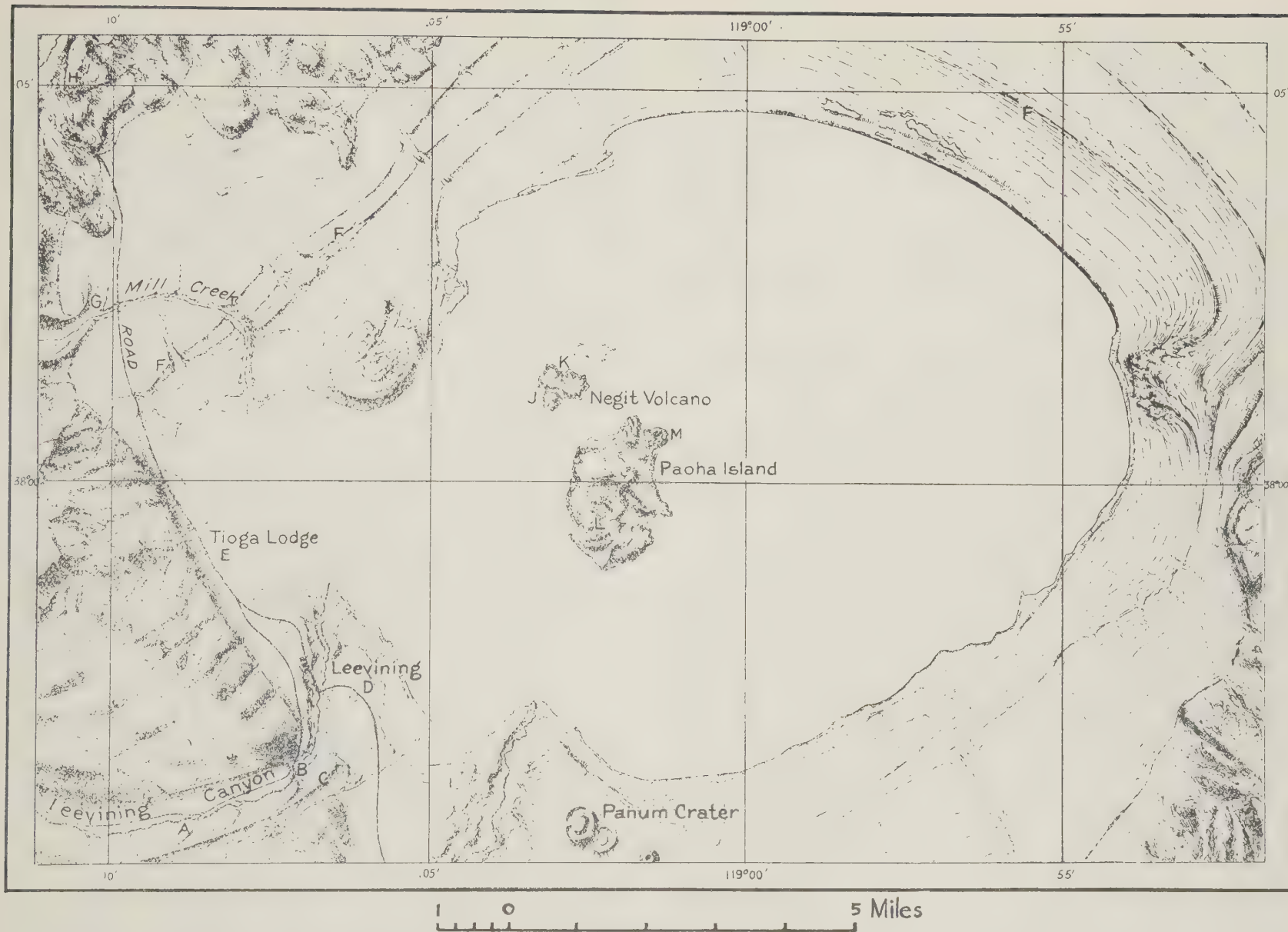


FIG. 57. Mono Lake on the east side of the Sierra Nevada below Tioga Pass. Around the lake are the terrace deposits and wave-cut cliffs left by former Lake Russell. *After I. C. Russell.*

about 650 feet above the present surface of Mono Lake. In places the terraces were eroded by waves into the Sierran bedrock or into moraines which had been left by glaciers descending from the great range; elsewhere they were constructed of sediment deposited while for a time the lake stood at various levels and then were exposed as the waters fell to lower positions. Most of the debris which tributary streams carried into the lake is silt (very finely divided rock fragments), the remainder being sand and gravel. There is almost no clay in the deposits. The lake terraces now are a rather desolate area covered principally by sage brush.

The small town of Leevining at the junction of the Tioga Pass road and Highway 385 stands on one of these terraces, a wide one, 380 feet above Mono Lake and the same terrace makes the broad expanse of Pumice Valley farther south.

Streams flowing from the Sierra Nevada into Mono Lake, such as Rush and Leevining, have cut gorges 300 feet deep into the terrace deposits since the recession of the valley glaciers evolved during the fourth glacial stage.

In the Mono Lake region on the Sierran side four glacial stages have been recognized by moraines left as the various glaciers receded. Records of the last two, the Tahoe and succeeding Tioga, are far better preserved than those of the earlier pair, for the later glaciers destroyed or greatly modified the earlier deposits.

Lateral moraines project from the mouths of the larger canyons, extending beyond the base of the Sierra Nevada as a series of crescentic ridges whose slopes are broad and culminate in narrow crests. Some of the embankments rise at least 800 feet above the lake terraces which they nearly surround. There are also terminal moraines belonging to the last glacial stage but they are small as contrasted with the lateral banks. The moraines are chiefly granitoid debris, including great boulders embedded in masses of sand and gravel. The extent of the morainal belt and the volume of debris included in it is striking testimony of the vigor of glacial erosion.

One of the most remarkable topographic features of this area is the anomalous horseshoe valley of Reversed and Rush creeks, which is partly occupied by four lakes, June, Gull, Silver, and Grant. The name Reversed Creek is appropriate, for the creek flows from Gull Lake toward the mountains rather than toward the low country as does the normal drainage; it joins Rush Creek at the bend of the horseshoe, and Rush Creek flows to Grant Lake in the western arm of the loop. June Lake has no outlet except a small drainage canal cut across the marshy ground separating it from Gull Lake.

The origin of this strange valley pattern has been explained in various ways. Two principal fault systems cross the area, an outer one which is the main boundary system along the eastern base of the Sierra

Nevada and an inner one which runs along the escarpments of Mount Parker, Mount Wood, and San Joaquin Mountain, and under the trough occupied by Silver Lake. This second system probably has been the more important in the evolution of Reversed Creek-Rush Creek canyon. It is assumed that two eastward flowing streams crossed the area and were separated by a low divide near the south end of present Silver Lake. A tributary of one of these streams, eroding headward along the weak crushed zone of the inner fault system, diverted the other stream into itself. The probability is that Rush Creek (the western stream) captured Reversed Creek which lies to the east because it had the advantage of working in less resistant rock. Whether or not

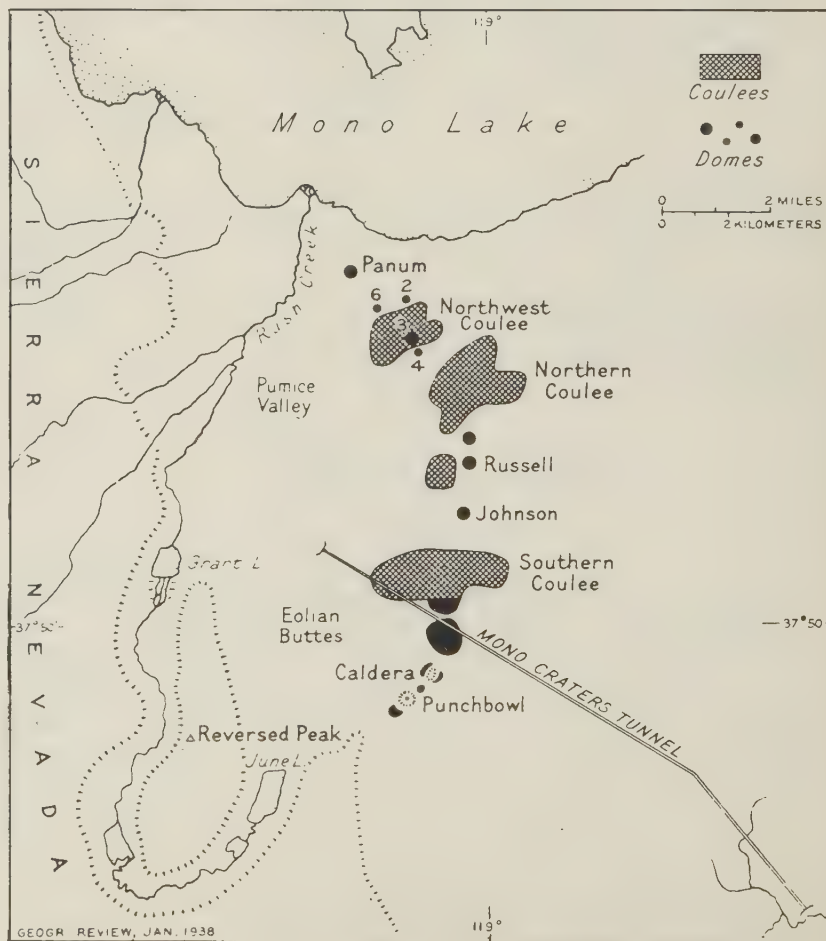


FIG. 58. Map of Mono cones and surrounding area. After W. C. Putnam.

the capture was made before the end of the next to the last (Tahoe) glacial stage has not yet been determined.

The problem of the reversal of drainage direction appears to be related to the relative resistance of the bedrock in the area and the relative erosional efficiency of the two branches of the Rush Creek glacier. Rocks in the June Lake area are more resistant than those about Grant Lake, hence glacial attack upon the former was less effective than on the latter. The June Lake branch of the Rush Creek glacier averaged about 2.2 miles in length, as compared with the Grant Lake arm which was only 1 mile; the latter not only was thicker (1,800 feet as compared with 1,300 feet), but had the advantage of being concentrated in a narrow, well-defined channel. Therefore glacial erosion was more successful in the Grant Lake than in the June Lake branch of the glacier. The depth of glacial erosion also is closely related to the fracturing of the rock, the trough at Silver Lake being deeper where the faulting and jointing has been most intense and shallower where the ice traveled over rock in which the joints are widely spaced, as immediately west of Gull Lake. Thus the valley was deepened less in the June Lake area and more around Grant Lake, causing the present Reversed Creek to flow in an abnormal direction as compared with other streams in the region.

Perhaps the most unique feature of the Mono Lake region is the range of volcanic mountains called the Mono Craters, extending from the south side of the lake for about 10 miles southward, and clearly visible from Highway 395. The highest of the mountains stands about 2,700 feet above the surrounding rolling plain and the range as a whole would be quite conspicuous were it not dwarfed by the enormous bulk and height of the Sierra Nevada a few miles to the west.



FIG. 59. Panoramic sketch of the west side of the Mono cones, showing cones, domes, and coulees. After W. C. Putnam.

The Mono Craters are a group of pumice cones in most of which have risen domes of obsidian (volcanic glass of granitic composition), some so bulky that they flowed over the cone walls, advancing upon the adjacent plain as short, steep-fronted and steep-sided flows, called *coulees*. The range, which is crescentic in groundplan bending toward the east, is divided into three nearly equal parts by the projection of

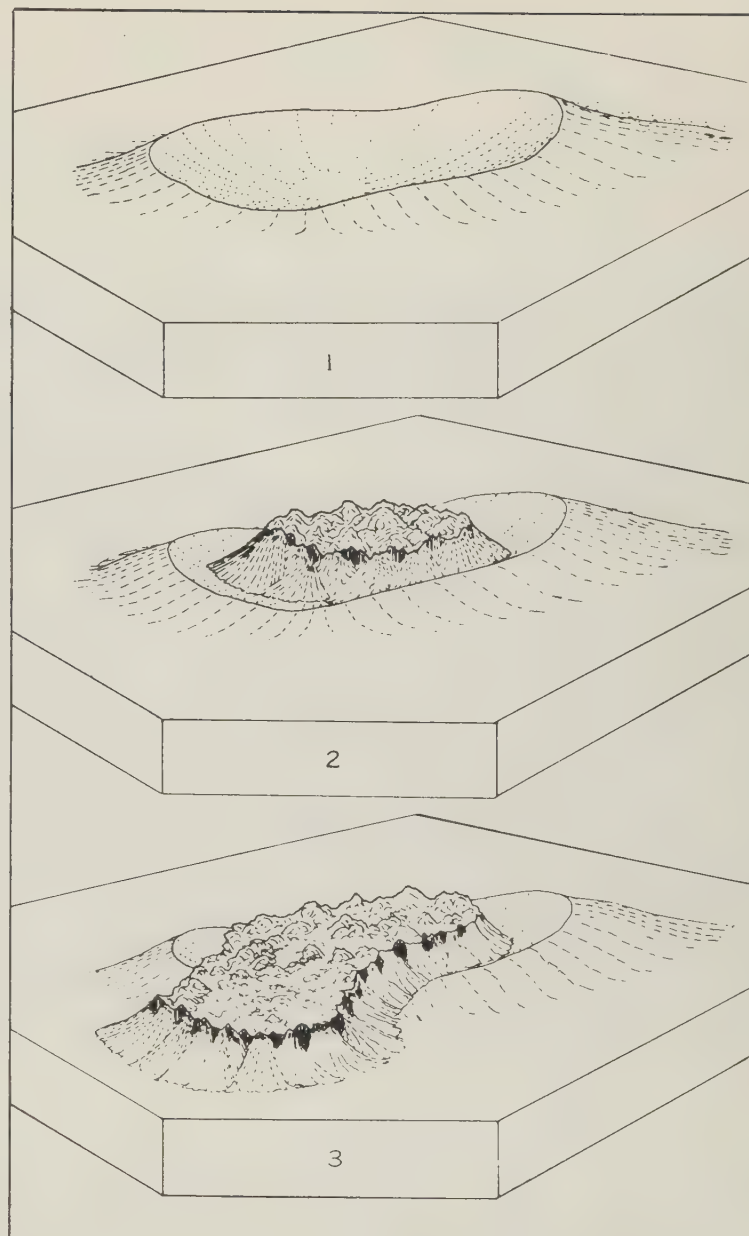


FIG. 60. Stages in development of the Mono cones, volcanic domes, and coulees. 1, Low cones formed by explosions of rhyolite pumice. 2, Rise of volcanic dome in crater of cone, either flush with cone rim or projecting far above it. 3, Too high dome elevation caused part of mass to overflow crater rim forming short, thick flow called a coulee, covered with blocks of obsidian. After W. C. Putnam.

the two largest coulees nearly at right angles to the trend of the range. The northern of these two principal coulees shows only on the eastern side of the mountains, but the southern is divided nearly equally between the two sides.

The Mono Range rises highest near its central part, where three turret-shaped domes of nearly equal size are present, the middle one forming the highest peak.

North of the northern coulee, there are five domes and two smaller coulees; south of the southern coulee are six domes and four large explosion pits. The northernmost dome is isolated from the rest of the range, standing about a mile from it and just south of Mono Lake. This cone and dome, which is called Panum Crater, is low, the dome rising about to the level of the crater wall, from which it is separated by a trench or moat.

The generation of most of the volcanic forms of the Mono Range has followed a definite sequence. At first explosions of moderate violence formed shallow, bowl-shaped depressions much resembling large shell holes. Highly gas-charged lava was blasted out building low explosion cones made of pumice fragments. Following the explosive episode, largely solid, cylindrical columns of obsidian rose in the craters, forming domes of various heights. If the domes were sufficiently elevated, they contained enough liquid—though very sticky—lava to cause the rising mass to spill over the rim of the cone, generating the coulees which in their outer parts are chaotic jumbles of angular boulders. In the north and south major coulees separate outpourings coalesced to form more extensive flows. When the domes ceased rising in the craters, most of the conduits were sealed. There was but one case of renewed explosive activity which produced the deep pit called the Caldera at the south end of the chain. This is a steep-sided double crater occupying the center of an obsidian dome extensively destroyed by explosion.

Great streams of talus coming from the higher domes have almost completely masked the pumice cones in which they rose. The obsidian boulders forming the talus were generated by fragmentation of the steep domes as they cooled and contracted and also by later frost wedging which has further disrupted them.

Two nearly complete pumice cones may be seen near the summit of the Mono Range between the southernmost of the three central domes and the south major coulee. The Devil's Punchbowl, near Highway 395, is a small but well-preserved explosion cone whose crater is about 1,200 feet in diameter and 140 feet deep; in the bottom is a small obsidian plug about 250 feet across, rising about 40 feet above the crater floor. Panum Crater, just south of Mono Lake, illustrates a somewhat more advanced stage of dome development. The cone is low, but stands out distinctly from the rolling plain round about. Separated

from its rim by a deep trench or moat is a steep-sided obsidian dome which rose after the preliminary explosions had formed the cone. The top of the dome, like that of others, is a wild jumble of spires, crags, and loosely piled blocks of obsidian.

The Caldera at the south end of the range, as previously noted, is the product of explosion at the end instead of the beginning of the volcanic cycle. This crater is comprised of a large, flat-floored bowl open at the west and a small, deep pit blown through the north wall of the main depression. Originally it was believed that collapse of the dome had developed the depressions, hence the name Caldera; but later studies indicate that explosions were responsible. The tops of the obsidian cliffs forming the walls of the Caldera are covered by 30 to 50 feet of volcanic ash and the secondary pit is clearly of explosive origin, differing from the larger one only in size. There is no evidence of faulting, which should be present if the basins had been formed by collapse.

The volcanic cycle which built the Mono Craters started in late Pleistocene time. Explosive activity began during the last high stand of Lake Russell for pumice is interlayered with lake sediments, but no lake shore lines cut the more recent cones, notably Panum Crater which is close to the lake and stands only 150 feet above its level. The explosion cones at the southwest end of the range were erupted through the floor of one of the small late Pleistocene lakes lying mainly to the east of the range. Pumice blasted out by the explosions mantles moraines of the last glacial stage, but there is no sign of activity today anywhere in the range.

Warner Mountains

A splendid example of a fault block range in northeastern California is the Warner Range, a narrow, rugged mountainous mass about 87 miles long which extends from southern Oregon across Modoc County, California, into Lassen County. On the east it projects slightly into Nevada. At the northern end, the range merges into a high plateau between Abert Lake and Warner Valley and does the same at the opposite extremity just east of the Madeline Plains in Lassen County. The width of the Warner Mountains ranges from 8 to 20 miles, the narrowest part being slightly north of Alturas, county seat of Modoc County. The highest peaks, located southeast of Alturas, are nearly 11,000 feet, but most are closer to 8,000 feet.

The eastern front of the range, rising abruptly from arid Surprise Valley, is a spectacular, battered fault scarp along the base of which runs the road leading north and south of Cedarville. The northern half of the western side, as far south as Fandango Valley, closely resembles the eastern front. Fandango Valley is a major embayment which almost cuts the range in two, but has no counterpart on the eastern side. South of this valley, the western front is much less imposing, since the faulting is complex and the mountains rise in a



FIG. 61. Panum Crater south of Mono Lake and part of the Mono volcanic range. In Panum Crater and the one immediately south, volcanic domes have risen about to the level of the crater rim from which they are separated by a narrow trench or moat.

series of steps, each representing a block bounded by faults. A splendid view of the western part of the Warner Mountains may be obtained along Highway 395 leading north and south of Alturas.

The southern half of the western front of the Warner Mountains differs widely from the northern. There is no conspicuous escarpment, only a long unbroken slope from the base to the crest of the range. The surface of this slope for the most part coincides with the uppermost layer of lava composing the mountains.

From the picture just drawn, it is evident that the northern end of the Warner Mountains is a horst or vertically elevated fault block bounded by battered scarps on both sides; also that the southern section is a tilted fault block with the great scarp on the eastern side. The change from the one to the other is gradual. The uplands of the horst are comparatively smooth lava-capped areas, little modified by erosion, which are being destroyed by canyons being eroded headward into them from both sides of the range.



FIG. 62. Panorama of the eroded fault scarp forming the eastern side of the Warner Range in eastern Modoc County. The western slope of the range is a gently inclined, not greatly dissected erosion surface. Showing at the base of the range is part of Surprise Valley. *Photo by C. W. Chesterman.*

West of Goose Lake Valley and the north part of Pit River Valley is an extensive plateau known as The Gardens. Most of its surface is a smooth lava cap but locally small domes of rhyolite and obsidian rise above it. Still farther west, toward the boundary of Modoc County, there has been much recent volcanic activity and large areas of the plateau are covered by lava flows, explosion cones, and other extrusive forms. This section is known as the Modoc Lava Beds or the Burnt Lava Country.

Surprise Valley east of the Warner Mountains is a larger trough than that on the western side. Along its eastern margin rises the Hays Canyon Range, which is bounded by a battered fault scarp, but one far less striking than the eastern declivity of the Warner Range.

The rocks composing the Warner Mountains are principally lava flows and fragmental deposits which lay in essentially horizontal position at the time of the elevation of the fault block. These volcanics were erupted during a long but intermittent cycle which saw a huge section of northeastern California and still greater territory in Oregon, Washington, Idaho, and Nevada turned into one of the most gigantic volcanic fields of the earth.

It is believed that prior to the deformation which produced the ranges and grabens of this region, an extensive rather even-surfaced plain existed. Below this plain the lava flows and fragmental deposits were essentially parallel with its surface. Over some sections very late basalt flows were erupted, covering them in places to depths of 600 feet.

Deformation, starting toward the end of the Pliocene or in the early part of the Pleistocene epoch, produced a broad dome with its crest in the Warner block; as it evolved the dome fractured. The Warner and Hays Canyon ranges rose, while Goose Lake, Surprise Valley, Long Valley, and other grabens moved downward. There does not appear to have been much compression outside of the broad doming, the principal deformation being the differential vertical dislocations. The evidence for the development of this breaking dome comes from the increase in elevation from the Gardens to the summit of the Warner Range and the decrease eastward from the summit of Hays Canyon Range to its base. In a north-south direction, the greatest height of the Warner Range is in its central part with decrease toward both ends. The arch in this direction, however, quite certainly resulted from differential elevation of blocks bounded by faults and not from

compression. The Warner Range, therefore, is a mosaic of fault-bounded masses which have behaved in different fashions as the deformation proceeded.

Indication of continued sinking of the grabens comes from the location of lakes against the base of the steepest escarpments, where apparently the movement is most active. If this dislocation were not still going on, erosional waste from the ranges which forms alluvial fans and aprons at their bases would long since have forced the lakes farther outward and the deepest parts of the grabens would be toward their centers. The broad playas of Surprise Valley, deposits formed in a lake which formerly lay against the base of the Warner Range, Lake Annia in Jess Valley, Alkali Lake in Long Valley, High Rocky Lake in High Rocky Valley, Abert Lake, and others hug the steep escarpments. All of this evidence testifies to the recency of evolution of the major features of this remarkable landscape.

Surprise Valley, the graben between the Warner Range and fault block mountains to the east, starts 7 miles south of the Oregon border on the east side of the Warner Mountains and extends for about 54 miles southward. An average width of about 8 miles is maintained over this distance, though there is narrowing at the northern and southern ends. At present there is no outlet from the valley.

Perhaps the most notable feature is evidence of series of large lakes called Surprise Lake, which existed during one or more of the recent glacial stages. These great bodies of water which reached a maximum depth of 550 feet not only filled practically all of Surprise Valley but overflowed a narrow divide at its southern end, covering

Duck Flats. Evidence seems to indicate that at least two lakes were separated by a time of aridity, when the valley became very dry and probably all of the water was evaporated. The old shore lines are indicated by wave-cut cliffs and terraces, and by delta and other deposits. The highest shoreline is particularly well marked and extends around the valley in virtually undamaged condition.

The Duck Flat extension spread mostly over a surface of basalt which probably already had on it a growing lake, for this area also is an enclosed basin. In Duck Flat the highest level shore line is best developed, indicating that at this stage the lake remained relatively stable for a considerable period. Whether the water overflowed barriers into other basins is not known, though this is quite possible.

As the water of Lake Surprise lowered, the Duck Flat section was isolated from the main body as is shown by an outlet gorge cut between the two with the slope toward Duck Flat. For a time two lakes existed with that in Duck Flat standing about 200 feet below that in Surprise Valley, but when Lake Surprise was still 200 feet deep, overflow through the gorge into Duck Flat ended and its lake probably disappeared rather soon because it seems to have been maintained principally by water from the larger body. Finally the main lake itself was completely evaporated.

On many maps of Surprise Valley, three large lakes are shown which are called by some Alkali Lakes and by others Upper, Middle, and Lower Lakes. The northern or Upper Lake when filled is a unit. Middle Lake also was a unit when it contained water, but, some years ago, it was divided by the construction of a causeway east from Cedar-



FIG. 63. Panorama of Fandango Valley, a structural depression obliquely crossing part of the Warner fault block range in eastern Modoc County. Cross faulting apparently has been the principal cause of the formation of the valley. *Photo by C. W. Chesterman.*



FIG. 64. Pinnacles eroded in volcanic rhyolite tuff in the Warner Mountains. Most of the rocks of the range are basalt flows. *Photo by C. W. Chesterman.*

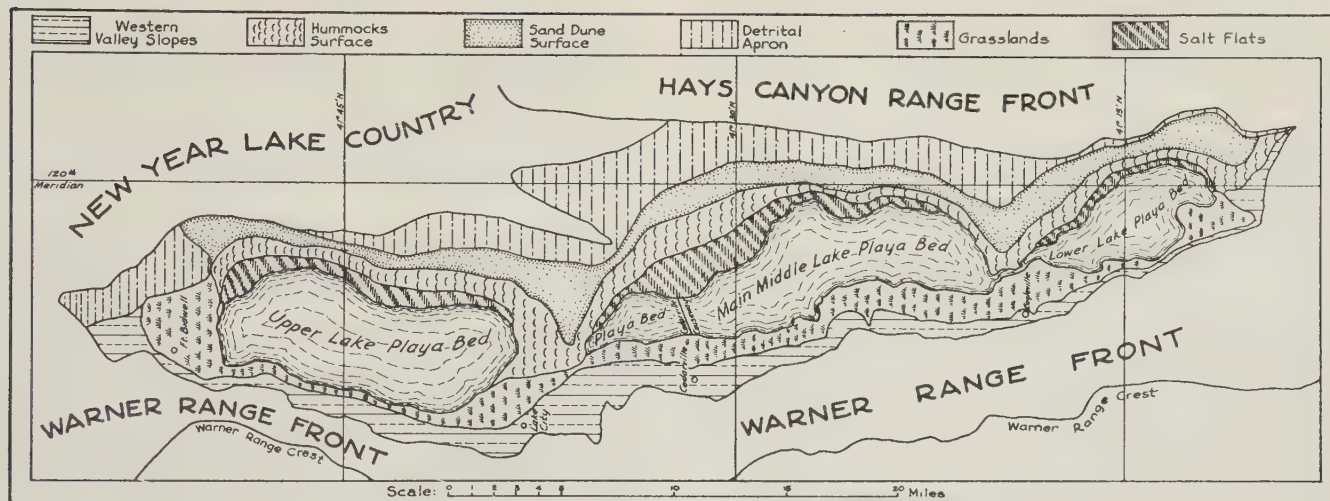


FIG. 65. Map of Surprise Valley and the adjacent Warner and Hays Canyon Ranges. After R. J. Russell.

ville, the principal town in Surprise Valley. The southern or Lower Lake, in contrast, is an aggregate of smaller lakes, each of which is a playa but does not become dry simultaneously with the others. Since the waters of the larger lakes evaporate so that only isolated depressions are filled, it has been customary to give names to the small residuals. Thus the term Eagleville Lake is much more significant in Surprise Valley than Lower Lake and refers to a small portion near the town of Eagleville. This lake is said to have dried up only once in the memory of many of the oldest inhabitants.

Upper Lake when filled is about 13 miles long and 4 miles wide, an overflow channel into Middle Lake preventing further growth. In normally wet years, it decreases to about half its major size during the dry season, but in dry years it disappears. In the winter the frozen surface of this lake often serves as a highway between Lake City and Fort Bidwell. When completely dry, the playa surface is also used for traffic. Upper Lake normally does not become as completely dry as the two lower ones.

Middle Lake is nearly as wide as the upper one and is 18 miles long. The northern 4 miles have been isolated by the Cedarville causeway and is dry most of the time during the summer. The main lower part generally contains water until early summer and one or two pools usually remain along its western margin.

Lower Lake is much smaller than either Middle Lake or Upper Lake. Toward the south is a broad, continuous playa but northward this is broken, chiefly because of wind-blown accumulations which form isolated basins. Nearly every year water overflows from Middle into

the Lower lakes, but during the summer most of the basins are dry. However, even in the driest years, a few depressions in the western side of the largest playa contain water coming from nearby hot springs.

Evaporation of the lakes is accompanied by westward movement of the eastern shoreline until finally no water is left. When the playa beds are exposed, they crack into blocks having an irregular hexagonal pattern. In the summer frequent wind whorls carry dust to heights of 1,000 to 3,000 above the playa surface, and more violent blows cause dust storms which obscure the landscape to elevations of 2,000 to 3,000 feet above the valley.

East of the playa beds salt and alkali coatings are abundant; elsewhere there are none. Along the eastern side of these salt flats there are hummocky areas which appear to be wind-blown accumulations of sand and dust with deposition starting mostly around sage brush. Small, actively migrating sand dunes are found east of this hummocky area. They do not exceed 30 feet in height, and their northeast-southwest crests with the steeper slope on the eastern side indicates predominantly southeast-blowing winds.

On the west side of the Hays Canyon Range there is a prominent alluvial apron having a slope in the steeper parts of at least 10 degrees. Recent fault scarps break the continuity of the apron in a number of places. Above the alluvial slope rises the eroded Hays Canyon fault scarp which is steeper, more barren, and more subject to considerable rockslides than is the Warner Range across the valley. These notable slumps and scars appear to be a product of the deficiency of vegetation over the upper slopes of the range which receive much less snow

and rain than do the Warner Mountains. The elevation of the two ranges is approximately the same and the rock formations are alike. At the ends of the Warner Range where the elevation is less and therefore vegetation not so prevalent, slide features are more common than in the higher part.

Along the Warner Mountains across Surprise Valley there also is a considerable alluvial apron, with steep slopes (up to 10 degrees) at and near the canyon mouths but decreasing farther out until they seem almost flat.

At various places in the Warner Mountains there are a number of landslide lakes which have been formed by the collapse of lava rim rocks overlying more easily weathered and eroded material. Under proper conditions where there is not too much protecting talus, the canyon walls are sufficiently exposed so that the resistant rims are undermined and masses eventually break loose, cascading into the bottom of canyons where they may form dams sufficiently durable to impound lakes for considerable periods.

One example, Clear Lake, located in Mill Creek Canyon 2 miles northeast of Jess Valley in the southeastern part of the Warner Range, is small and not over 90 feet deep. It has been formed by two slides, one from each side of the canyon a thousand feet deep. The slide scars are so fresh and the delta formed by the stream flowing into the lake is so small that the barrier probably was not formed more than 100 years ago. Blue Lake, 10 miles farther south, is similar in origin and very recent, but its waters are impounded by a single slide. Both Clear and Jess lakes drain to the Pit River. On the eastern side of the range, 7,400 feet above sea level, is Lost Lake, also in a deep canyon; the scar of the slide which holds back its waters is much less distinct than those of the lakes previously mentioned and the delta plain formed by the stream supplying the lake is half again as large as the water surface, hence it is considerably older.

Jess Valley is believed to be a filled, drained, older, and larger landslide lake in the valley of the Pit River between Clear and Blue Lakes, where the river flowing from the west base of the Warner Range cuts a gorge through another up-faulted lava bed block of lower altitude. The nearly even surface of the valley is about 6 miles long and more than 2 miles wide. The slide which dammed up the river is of enormous size.

Eagle Lake, 30 miles northwest of Honey Lake and therefore south of the Warner Mountains, stands about 5,100 feet above sea level, is

12 miles long and 2 to 4 miles wide. The barrier forming it appears to be a landslide on the southeast side. The level of the lake rises and falls without regard to rainfall and when it sinks streams flow from the outer slope of the barrier and are tributary to streams entering Honey Lake. This indicates the porous nature of the dam, a feature characteristic of landslide jumbles, but it also shows that the passages through which the water emerges are alternately opened and closed.

REFERENCES

- Baker, C. L., Physiography and structure of the western El Paso Range and the southern Sierra Nevada: Univ. California Dept. Geol. Sci. Bull., vol. 6, pp. 117-142, 1912.
- Blackwelder, Eliot, Lake Manly, an extinct Lake of Death Valley: Geog. Rev., vol. 23, pp. 464-471, 1933.
- Blackwelder, Eliot, Yardangs: Geol. Soc. America Bull., vol. 45, pp. 159-166, 1934.
- Gale, H. S., Notes on the Quaternary lakes of the Great Basin with special reference to the deposition of potash and other salines: U. S. Geol. Survey Bull., vol. 540, pp. 540, pp. 399-406, 1914.
- Kesseli, J. E., The origin of June, Gull, and Silver lake valleys, Mono County, California: Jour. Geology, vol. 40, pp. 726-734, 1932.
- Knopf, A., and Kirk, E., A geological reconnaissance of the Inyo Range and the eastern slope of the Sierra Nevada, California: U. S. Geol. Survey Prof. Paper 110, 1918.
- Lee, C. H., An intensive study of the water resources of part of Owens Valley, California: U. S. Geol. Survey Water-Supply Paper 294, 1913.
- Louderback, G. D., Period of scarp production in the Great Basin: Univ. California Dept. Geol. Sci. Bull., vol. 15, pp. 1-44, 1924.
- Louderback, G. D., Morphologic features of Basin Range displacements in the Great Basin: Univ. California Dept. Geol. Sci. Bull., vol. 16, pp. 1-42, 1926.
- Mayo, E. B., and others, Southern extension of the Mono Craters, California: Am. Jour. Sci., 5th ser., vol. 32, pp. 81-97, 1936.
- Noble, L. F., Structural features of the Virgin Spring area, Death Valley, California: Geol. Soc. America Bull., vol. 52, pp. 941-1000, 1941.
- Putnam, W. C., Quaternary geology of the June Lake District, California: Geol. Soc. America Bull., vol. 80, pp. 1281-1302, 1949.
- Russell, I. C., Quaternary history of Mono Valley, California: U. S. Geol. Survey Eighth Annual Report, pp. 26-394, 1889.
- Russell, R. J., Landslide lakes of the northwestern Great Basin: Univ. California Publ. in Geography, vol. 2, pp. 231-254, 1927.
- Russell, R. J., The land forms of Surprise Valley: Univ. California Publ. in Geography, pp. 323-358, 1927.
- Russell, R. J., Basin range structure and stratigraphy of the Warner Range, northeastern California: Univ. California Dept. Geol. Sci. Bull., vol. 17, pp. 387-496, 1928.
- Von Engel, O. D., Ubehebe Craters and explosions breccias in Death Valley, California: Jour. Geology, vol. 40, pp. 726-734, 1932.

MOJAVE DESERT

MOJAVE DESERT

As used herein the term Mojave Desert province applies to the area in southern California which has the following boundaries: the Basin-Ranges province on the north (see pl. 2); the southern end of the Sierra Nevada and the Tehachapi Mountains on the northwest; on the southwest the Sawmill and Liebre Mountains, the Sierra Pelona, and the San Gabriel Mountains; on the south the San Bernardino Mountains and the Colorado Desert. The northern margin is difficult to determine, as the Mojave Desert merges into the Great Basin. However, an approximate line has been chosen between the southern part of the Great Basin where the mountain ranges are markedly parallel and the region to the south where the ranges are lower, more deeply dissected, and lacking in conspicuous parallel arrangement. This east-west line falls between the Nopah and Kingston Ranges and runs west to El Paso Mountains north of the mining camps of Randsburg and Johannesburg (see pl. 2).

The Mojave Desert is characterized by a small amount of annual precipitation and low humidity. The temperatures are moderately high in the winter and extremely high in the summer, with notable daily range. At certain times of the year strong winds blow across the region. Precipitation increases with altitude, but the increase is far from uniform, the known differences in part at least resulting from position of a locality with respect to the rain-bearing winds.

Faulting has been conspicuous in the Mojave Desert province and has been the prime control of separation of high- and low-standing areas. Most notable of the fault systems is the San Andreas which lies along the north base of the San Gabriel Mountains. It shows conspicuously from the air as an almost continuous succession of long, narrow basins separated by elevated areas which undoubtedly are small fault blocks that have risen as the basins have subsided. The last known dislocation along this section of the rift occurred in 1857.

Another prominent fault system, the Garlock, is found along the southeast face of El Paso Mountains. Near the town of Garlock, it cuts a large alluvial fan; 5 or 6 miles to the northeast, near Goler Well, there are large depressions formed by dropping of blocks of ground along the fracture zone. The scarps are so fresh that the dislocation must be rather recent. Northeast of El Paso Mountains, the Garlock fault shows along low hills on the south border of Searles Valley. East of the Slate Range, a long, narrow valley—with Leach Point Mountains rising steeply on the southern side and a more gentle slope on the northern—suggests the same fault, which may continue as far as the Avawatz Mountains. However, the faults in the Avawatz Mountains may belong to another series. Southwest of El Paso Mountains there is a marked escarpment on the southeast side of the Tehachapi Moun-

tains which is in almost perfect alignment with the southeast side of El Paso Mountains, containing sag ponds and other features showing that the Garlock fault continues in that direction.

The San Andreas rift and the fault along the front of El Paso and Tehachapi ranges bound a conspicuous area having the form of an arrowhead, whose point is at the western edge of the desert. This area has within it only low, scattered hills but no large mountains.

South of the Garlock fault, the strikingly parallel ranges and basins so characteristic of most of the Basin-Ranges province are less apparent, and the arrangement in most of the Mojave Desert is much less clearly defined. However, there is abundant evidence of faulting in many places, and major landscape features have been evolved by movements along the faults, many of which seem to be rather short, but have been zones of much displacement.

Areas where faulting seems to have exerted notable control in landscape evolution are Lane Mountain and the connected hills about 15 miles north of Daggett; the basins containing the playas known as Soda, Silver, and Silurian dry lakes, with the adjacent mountains extending from the Soda Lake Mountains north to Avawatz Mountain and the New York-Providence Mountains. Others are a series of north-westward trending, short, parallel ridges north of Bagdad and Amboy, the highest of which is Old Dad Mountains, and a more or less continuous range south of the Atchison, Topeka & Santa Fe Railway, extending from near Daggett for many miles southeastward and including the Bullion and Sheep Hole Mountains.

Evidence is insufficient to determine the age of much of the faulting but some certainly is of very late date and some faults are still active.

Because most of the Mojave Desert has not been studied geologically, the history of its landscape is imperfectly known.

The Afton Basin is an enlargement of the valley of the Mojave River about 40 miles east of Barstow in the Mojave Desert. This area is one of rather even-surfaced alluvial deposits—both low sloping alluvial fans and basin sediments—above which rise isolated mountains of moderate elevation. The basin appears at one time to have been undrained, and this condition probably continued into middle Pleistocene time. Later the Mojave River, flowing from the San Bernardino Mountains, advanced into the region where its waters were impounded to form Lake Manix, named for a station on the Union Pacific Railroad. An almost completely enclosed embayment of this lake occupied the Afton Basin. Later on, probably because of erosion by its outlet, this lake was drained and the sediments deposited therein have been eroded rapidly by the Mojave River and its tributaries.



FIG. 66. Sag ponds, basins, and buttes (center) formed by San Andreas fault near Palmdale, Mojave Desert. *Photo courtesy Fairchild Aerial Surveys, Inc.*



FIG. 67. Panorama of the Chuckawalla Mountains, Riverside County, a fault-block range in the Mojave Desert. *Photo by C. W. Chesterman.*

Field evidence shows that the basin actually contained two lakes, the earlier of which disappeared because of an intervening dry epoch. Then a third much smaller lake developed in Mojave River canyon after the draining of the earlier lake water and dissection of the sediments which had been deposited in it.

The first lake apparently had a fluctuating level determined by the balance between inflow and evaporation. For a time it was relatively fresh as the presence of fish remains and mollusk shells proves, but later it became distinctly saline as is shown by gypsum crystals in some of the sediments. Manix and Afton Basins during this interval seem to have contained all the water brought in by the Mojave River, for had the lake overtopped the divide separating them from the much lower Soda Lake basin to the east, the outlet would undoubtedly have been cut down sufficiently to have destroyed Manix Lake. The first lake lasted sufficiently long for its waves to build large and rather conspicuous gravel bars along the northeast side of the basin. The moister interval which made possible the growth of this water body probably coincided with the earlier (Tahoe) part of the fourth glacial stage.

Then the climate seems to have become more arid, the Mojave River no longer reached Afton Basin, and the lake water evaporated leaving a playa floored by clay. Some minor alterations in the playa surface were caused by erosion and deposition.

Again moister climate returned, this during the later (Tioga) part of the fourth glacial stage, and the second Lake Manix developed. The surface rose about 20 feet higher than that of the first lake, and the waves, besides making important additions to the gravel bars, cut small cliffs and terraces. The new lake overflowed eastward into Soda Lake Basin. The outlet dropped about 875 feet in 14 miles and hence was a powerfully eroding stream which not only cut a deep notch on the

east side of Soda Lake Basin, but with its tributaries so extensively eroded the floor on Manix Lake Basin that only small remnants of the bottom deposits of the first lake remain as divides between the gullies. The gravel bars, being farther back from the river and more porous in composition, were less affected; they are still almost intact for perhaps half their original length.

Some time after this badland topography was evolved, a third lake appeared in the Mojave River valley, but because its surface was not more than 1,637 feet above sea level, it did not extend into Manix Basin, was much smaller than its predecessors, and also was shorter lived. The cause of the development of this lake has not been discovered. Since a continuous gorge had been eroded from Soda Lake Basin into Manix Basin, the only reasonable explanation is that this canyon was blocked in some manner, but no evidence of such barrier remains.

If the third lake was formed in the manner indicated, it had no climatic significance; the first two, however, seem to be definitely associated with the third and fourth glacial stages.

In the Mojave Desert, there are a number of places where granite and other granitoid rocks exposed in mountain blocks have been eroded to form rather smooth, dome-like areas with craggy masses of the bedrock standing above the general level and detached boulders, some of large size, scattered over the surface. The ragged appearance of the ridges and the boulders has been developed by weathering along closely spaced joints. Such domes range from 3 to more than 8 miles across and their high points stand from 500 to 2,000 feet above adjacent lower land. Good examples may be seen at various places along Highways 66 and 91 east of Barstow. This peculiar landscape apparently results from the progressive erosion of an elevated fault block in which granite forms a considerable part of the bedrock.



FIG. 68. The Moapi, volcanic necks of rhyolite in the central part of the Turtle Mountains, eastern San Bernardino County. *Photo by C. W. Chesterman.*



FIG. 69. Turtle Mountains near Carson's Well, eastern San Bernardino County. The volcanic rocks in which the jagged landscape has been eroded overlie ancient granite that produced the more subdued forms in the foreground. *Photo by C. W. Chesterman.*



FIG. 70. West side of Rattlesnake Canyon. An eroded fault-block mountain in the Mojave Desert. Bedrock is granite; ragged topography results from weathering and erosion along closely spaced joints. *Photo courtesy National Park Service.*



FIG. 71. Parker dam across the Colorado River. The dam impounds a long, narrow lake, from which water is conducted by the Colorado Aqueduct to a storage reservoir near Riverside. From there, it is distributed to various parts of the Los Angeles Basin and San Diego. *Photo courtesy U. S. Bureau of Reclamation*



FIG. 72. Panorama of the north part of the Turtle Mountains, eastern San Bernardino County. *Photo by C. W. Chesterman.*

Along the California border with Nevada a large man-made lake lies behind Parker Dam situated in one of the canyons of the Colorado River about 16 miles north of the town of Parker on the Arizona side of the river. The great stream has excavated this canyon through one of the fault-block ranges of the Mojave Desert, apparently keeping pace with the elevation of the block as it has done in crossing various other ranges. The dam which rises about 300 feet above the surface of the water has impounded a long, narrow lake—a beautiful sight in an otherwise desert land. From this reservoir water is hoisted by electric power brought from the great generating plant at Hoover Dam. Five lifts are necessary to carry it over a divide about 1,600 feet above the reservoir surface. From this point, a transporting system, the Colorado Aqueduct, carries the water down slope across desert basins and by tunnels through mountain ranges to a main storage reservoir about

7 miles southeast of Riverside. From the reservoir, mains and canals lead to various parts of the Los Angeles region and also to San Diego.

Parker Dam can be reached by an oiled road which branches off from Highway 95 about half way between Needles and Blythe.

REFERENCES

- Baker, C. L., Notes on the later Cenozoic history of the Mojave Desert region in southeastern California: Univ. California Dept. Geol. Sci. Bull., vol. 6, pp. 333-383, 1911.
- Blackwelder, Eliot, and Ellsworth, E. W., Pleistocene lakes of the Afton Basin, California: Am. Jour. Sci., vol. 31, pp. 453-463, 1936.
- Davis, W. M., Granitic domes of the Mojave Desert: San Diego Soc. Nat. Hist., Trans., vol. 7, pp. 211-258, 1933.
- Foshag, W. F., Saline lakes, Mojave Desert, California: Econ. Geology, vol. 21, pp. 56-64, 1926.
- Thompson, D. C., The Mojave Desert region: U. S. Geol. Survey Water-Supply Paper 578, 1929.

COLORADO DESERT

COLORADO DESERT

The Imperial and Coachella valleys are parts of a great depression of roughly V-shaped groundplan occupying a section of southeastern California known as the Colorado Desert province. This immense structural trough has its apex to the north not far from where the San Jacinto and San Bernardino Mountains meet at San Geronio Pass through which goes Highway 60 on its way eastward and then southeastward from Banning. The trough opens to the southeast where it is continuous with the larger and much deeper depression occupied by the Gulf of Lower California. Rising more or less abruptly from the southwestern and northeastern sides of the Imperial and Coachella valleys are bold mountains: the Peninsular Ranges border the southwestern margin while the southeastern portion of the San Bernardino Mountains of the Transverse Ranges province and various elevated blocks belonging to the Mojave Desert province lie along the northeastern side.

The climate over the depressed area is desert, being characterized by extremes of heat and dryness, for the Imperial Valley section is the hottest part of the United States and one of the hottest in the world. Ranges of temperature also are extreme as is characteristic of all such regions. The highest recorded temperature was 130°F., the lowest 22°F. Rainfall ranges from 1.10 inches annually at Ogilby, a small settlement in the far southeastern corner of the Imperial Valley, about 16 miles northwest of Yuma, Arizona, to 3.53 inches at Palm Springs near the northwestern end of the Coachella section. Most of the moisture falls in December, January, and February; in the Salton Sea region the month of June is practically rainless.

The Salton Basin is the southeasternmost section of the Imperial-Coachella trough and, though now separated, it is continuous with the depression under the Gulf of Lower California. At one time the gulf extended about 125 miles north of its present limit and one arm projected into the present Imperial Valley, a considerable section of which lies below sea level. The Colorado River discharged into this expanded gulf head north of the Mexican border as today it does into the shortened gulf south of this boundary. Near the border between the United States and Mexico, the river built a huge delta, the landward part of which finally rose above water level as a delta plain that eventually extended across the gulf isolating the northern part and impounding its waters as a lake having no connection with the ocean. As in most of southern and southeastern California, the climate in recent time has become increasingly arid causing the drying up of the lake and the conversion of the whole of the Imperial-Coachella depression into a desert.

The area of the Imperial-Coachella trough is considerably greater than that of other similar areas in California but the major features of the landscape are quite similar. The central part of the Salton Basin is rather flat. In a number of places bedrock masses project above the sedimentary fill, as for example Borego, Superstition, Carrizo, and Cargo Muchacho Mountains, Indio Hills, Pilot Knob, and a number of volcanic buttes 100 to 200 feet high south of Salton Sea.

Along the borders of the Salton Basin, there are extensive badland areas, as for example in the Mecca and Indio Hills near the two towns of those names on the east side and south of the Santa Rosa Mountains, around Seventeen Palms, and in the valley of Carrizo Creek on the west side. Smaller areas are numerous.

Badlands are areas characterized by a labyrinth of gorges separated either by round-crested or sharp-crested ridges. They are a product of the various phases of sheet and flash flood erosion in weak rock or rock mantle unprotected or insufficiently protected by vegetation. While best developed in arid lands, they are found also in humid places where for one reason or another the plant cover has been removed or seriously depleted. Badlands are among the most intricately sculptured landscapes.

The arroyos or dry washes generally are V-shaped in cross section, though some of the larger are flat-bottomed. The walls may rise almost vertically or may flare outward at various angles. In this region, where such landscape has been developed in nearly horizontal strata, vertically walled, flat-bottomed gorges predominate, and between them are nearly flat-topped divides rather than the more normal rounded or sharp-crested ridges. It is believed that this shape results from the speedy erosion by infrequent flash floods which represent the accumulation in brief time of great volumes of run-off. The torrential rain falls too fast for any great volume to sink into the ground, hence landsliding of water-logged masses from the walls rarely occurs.

In folded rocks, as in the Indio and southwest part of the Mecca Hills, the dry washes follow the outcrops of weak layers in which narrow, V-shaped gorges have been cut while in between are narrow ridges developed in resistant strata.

Wind erosion and deposition in this and other desert regions of California are no match for the effects of running water, but many sections show evidences of both.

Sand dunes are rather abundant in the Imperial and Coachella Valleys, particularly in the Salton Basin. The Sand Hills, running from past the Mexican border northward for 40 miles somewhat beyond the little settlement of Amos is the largest dune patch in

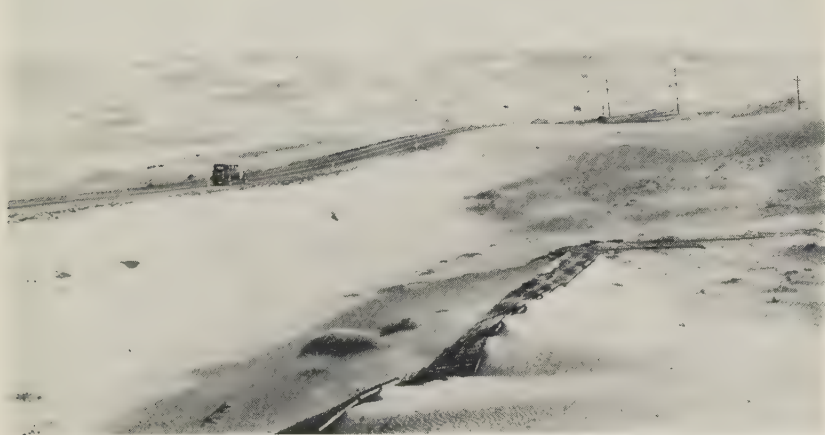


FIG. 73. New highway and old plank road crossing the sand sea in the southeastern part of the Imperial Valley. The main highway is sometimes blocked by drifting sand. *Fancher's Fotos.*

California and one of the largest in the United States. The belt ranges from 2 to 6 miles in width, forming a prominent barrier roughly paralleling the trend of the great trough. The crests of some of the dunes rise 200 to 300 feet above their surroundings. Highway 80 crosses this most interesting area and is blocked on numerous occasions by the drifting sand and an old, now abandoned corduroy road has been extensively buried.

Dunes are built principally by violent winds such as are common in desert areas and are best developed where the direction of blow is more or less uniform. Study of the Sand Hills shows that the winds responsible for their formation have come chiefly from the southwest, west, and northwest. West of the Sand Hills there is a nearly level plain 3 to 20 miles wide covered practically everywhere with sand which in places has piled into small dunes. However, over most of the plain is a thin coating of gravel consisting of fragments about the size of peas and evidently too heavy for the wind to move. This entire deposit is a beach formed when the lake was present in the Salton Basin. Probably the Sand Hills began to develop as the beach was formed and the supply of sand was being constantly increased. The dunes have migrated to their present position as the wind continued to blow over them driving the sand eastward, leaving the larger fragments behind. When this migration occurred is uncertain but land surveys made in 1856 show very little difference in form and position of the dunes from the present. There does, however, seem to be some movement of the hills towards the southeast.



FIG. 74. Old plank road in southeastern part of Imperial Valley. Sand has partly blocked the road. *Fancher's Fotos.*

In the Coachella Valley, north of Indio, there are extensive areas of shifting sand which are called *drifts*, but only around Indian Wells are there large dunes, which are formed by strong winds blowing from the northwest down San Geronio Pass into the heated lowland. In the pass itself there are great drifts of sand piled on the east sides of all rocky spurs projecting from the San Jacinto Mountains. Drifts are distinguished from dunes by being less sharply defined land forms.

Southwest of the Salton Sea, between McCain and Kane Springs, there is an area where small crescentic dunes called *barchanes* are well developed. These sand hills appear to evolve where the wind blows quite constantly from one direction and the supply of sand is rather meager. The barchanes are strongly unsymmetrical in cross section, with the gentle slope oriented in the direction from which the wind blows. The horns of the crescent, like the steep side, lie in the opposite direction. The sand forming the dunes apparently comes from an old beach, practically all of the sand having been used up in making the dunes. Some of the barchanes are not more than 300 feet from point to point of the horns, others measure about 1,000 feet. Many of these dunes travel in the direction toward which the wind blows, others have been essentially stationary for considerable periods of time. Those in the Imperial Valley have not changed position materially for the last 10 or 15 years, but this is quite a brief interval.

In San Felipe Valley in the same general region where the barchanes occur, there are *spring-formed dunes*. These develop in sandy areas where rising seep water allows growth of vegetation on accumulating



FIG. 75. Sand sea in the southeastern part of Imperial Valley west of Yuma, Arizona. *Photo courtesy Spence Air Photos.*



FIG. 76. View of the San Bernardino Range in the Transverse Ranges Province (foreground) ; San Geronio Peak, the San Jacinto Range, in the Peninsular Ranges Province (background) ; and the Coachella section of the Imperial Valley graben of the Colorado Desert Province. *Photo courtesy Fairchild Aerial Surveys, Inc.*

sands. The sand may pile so high that the water cannot rise through it, and the spring is completely sealed. The core of the dune is a black, mucky mass of soil and decayed vegetation. Kane Spring, which occupies a mound about 30 feet high and several hundred feet in diameter, is an example. At the top is a sunken marshy area an acre or two in extent from which water seeps eastward.

Peculiar dunes having a serpentine pattern occur on Superstition Mountain west of Westmorland on Highway 99 and are elongated parallel to the long axis of the mountain. They are found on both sides and apparently shift back and forth over its crest as wind direction changes. Frequently they blockade canyons, forming temporary basins behind them.

In various parts of the Imperial and Coachella Valleys, great numbers of irregular *sand drifts* have formed about clumps of vegetation, rock piles, and other obstructions.

One of the notable features of the Salton Basin is an old shore line which stands 40 to 50 feet above sea level, encircling the Imperial Valley including the Salton Sea, that part of the Coachella Valley south of Indio, and extending south of the border into Mexico. On the west side of the Salton Basin and throughout the Coachella Valley, the beach at most places consists of a sand ridge a few feet high, though its character varies somewhat with the rocks on which it was formed. In the sand are found many small, well preserved fresh-water shells. Near Fish Springs the shore line of the lake was granitoid rock and there is no beach deposit like that just described. Instead the shoreline is marked by an encrustation of the massive, limy rock called *travertine* which in places is several feet thick. This deposit, formed from the evaporation lake water, makes a white zone conspicuous from a considerable distance.

On the east side of Imperial Valley and as far north as Frink Spring, there is an almost continuous wave-cut cliff 10 to 30 feet high, with various amounts of sand forming the beach at the base of the cliffs.

All of these features show the presence of a large lake as one of the very recent features of this now desert basin. The shells indicate that the water was fresh or nearly so, hence the lake must have been supplied by the Colorado River which at that time apparently discharged into it rather than into the Gulf of Lower California, though overflow from the lake very likely went into that arm of the ocean. This lake, Lake Cahuilla, may have represented the gradual freshening by the Colorado of the arm of the Gulf of Lower California cut off by the building of the river's delta plain. On the other hand, the salt water may have dried up and the basin later supplied with fresh water from the river. Whatever is true, Lake Cahuilla lasted until very late time; its waters may have remained until 300 or 400 years ago. There also is some evidence that the basin may have been occupied by fluctuating

lakes for a long time and that on some occasions the water disappeared by evaporation, later to be replaced by overflow from the river.

The basin is known to have been comparatively dry from the time of the Spanish discoveries to the time of the great floods of the Colorado (1904-07) which created the present Salton Sea.

As the agricultural value of much land in the Imperial Valley became increasingly apparent, the problem of supplying sufficient water for irrigation became a pressing one. In 1900 work was commenced on a canal system to bring water from the Colorado River into the basin, and at that time the name *Imperial Valley* was chosen to lure settlers to this desert land.

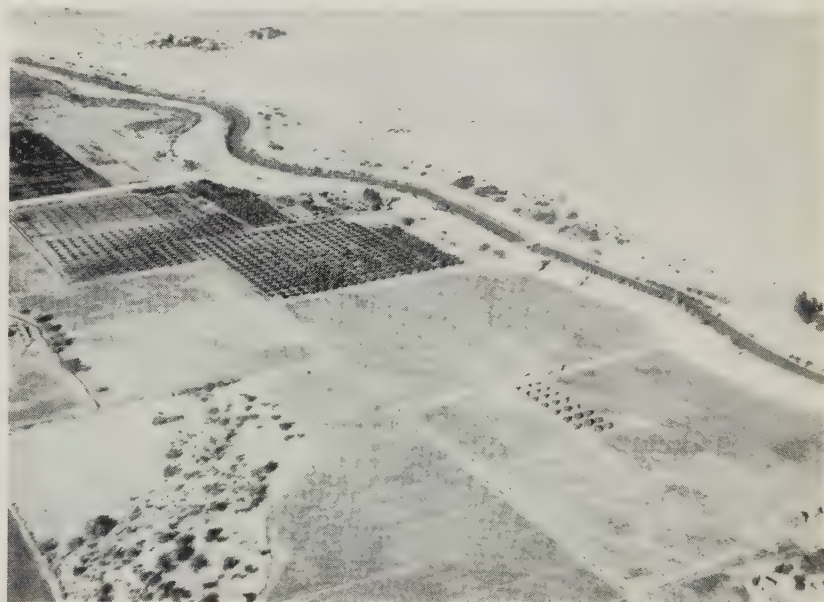


FIG. 77. View of Imperial Valley, showing the prolific crops which can be raised in much desert soil if water is available. Photo courtesy U. S. Bureau of Reclamation.

The transfer of water from the great river to the Salton Basin seemed quite simple. For years the Colorado had spilled its flood waters into the basin through two rather well-defined channels, Alamo and New Rivers. The slope from the river down the delta plain into the Salton Basin is greater than that toward the Gulf of Lower California. The California Development Company, which built the irrigation system, constructed its intake near Pilot Knob, an isolated mountain projecting above the alluvium of the delta plain about 10 miles west of Yuma, Arizona. The water was diverted through a gap excavated along the side of the river, and was led through a canal



FIG. 78. Imperial Valley and Salton Sea. The Salton Sea has attained its present size primarily as the result of great flows from the Colorado River in 1905 and 1906. *Photo courtesy Southern Pacific Railroad.*

which crossed the Mexican border and then went back into the Salton Basin some distance away. Later, because of too rapid silting in the canal, another intake was cut on the Mexican side of the border.

The flood danger from the Colorado was then not well understood and no proper preparation was made to take care of the river at high water. In the spring of 1905 several unusually high floods materially widened the break made in the river bank for the canal and these floods also carried away dams built to seal off this intake. By summer time when the highest water stage is reached, too much water was being diverted toward the Imperial Valley through the canal and spilling over its banks, where it wasted and began the formation of the Salton Sea. The irrigation company, involved in financial difficul-

ties, had placed itself under obligation to the Southern Pacific Railroad which finally took charge of the river control. Efforts were made to dam up the intakes, but successive floods carried these structures away.

Growth of the Salton Sea forced the railroad to move its main line to higher ground a dozen times and threatened to engulf all of the irrigable land of the Imperial Valley. The water sweeping into the basin eroded wide gorges into the soft alluvium, in which are the present channels of New and Alamo Rivers.

After most strenuous effort and great expenditure, the Southern Pacific succeeded in closing the break in November 1906, but a flood in the following month destroyed the repairs and the work had to be



FIG. 79. View of north end of the great Coachella-Imperial Valley graben showing the bordering San Jacinto Range on the left and the San Bernardino Mountains in the background. *Photo courtesy Fairchild Aerial Surveys.*



FIG. 80. Colorado River flowing over its delta plain west of Yuma, Arizona. The building of the combined delta and delta plain has shortened the Gulf of Lower California by at least 125 miles and has isolated the Imperial Valley graben which formerly was invaded by gulf water. *Photo courtesy Spence Air Photos.*

done again. Finally, aided by reduction of the flood waters, the river was sealed off and the valley rendered temporarily safe. However, what the river had done many times it could repeat, hence agitation started for the development of a flood-control project farther up the Colorado. This finally was undertaken and Hoover Dam now holds in

check by far the greater part of the Colorado's floods. Relatively little water comes in below this barrier.

In the evolution of the Imperial-Coachella trough and the bordering ranges, faulting has played a paramount role. The depression is part of a very large graben which extends southeastward beyond the

boundary of the Imperial Valley, while the ranges bordering on the east and west quite evidently have been elevated as the graben has sunk. Along the north side of San Gorgonio Pass and extending southeastward into the basin is the San Andreas rift. It probably is continuous with a fracture zone extending along the northeast side of the Indio and Mecca Hills, both of which apparently have been elevated by movements along this section of the fault. These low hills rise from the basin floor and are separated from the higher mountains to the northeast by a series of valleys and saddles. North of Indio, the northeast side of the Indio Hills is quite steep, though not more than 200 or 300 feet high, and is the most clearly defined fault scarp in this section. West of Dos Palmas the scarp is merely a low bluff. The fault probably passes north of low hills near Palm Springs Station; to the southeast it appears to extend at least as far as a low hill near Durmid which probably was uplifted in manner similar to the hills farther north. The same rift may continue as far as the Mud Volcanoes southeast of Salton Sea, and on past the Mexican border. Much of this is speculation because of the cover of sediment which makes positive identification virtually impossible.

On the southwest side of the basin there are faults of two ages trending in somewhat different directions. The intersection of these systems has caused the irregularities in the outline of the western border in which great mountain salients like the Santa Rosa Mountains, the Vallecito and Fish Mountain spur, and the mountainous projections along the Mexican border are separated by deeply re-entrant valleys like those of San Felipe and Carrizo Creeks.

If this structural picture is correct, the older of the two fault systems trends about 10 degrees north of west and is responsible for three spectacular escarpments, one forming the east base of the San Jacinto Mountains and passing up Palm Canyon, the second on the west side of Borego Valley, and the third extending from Agua Caliente Springs southward up Carrizo Gorge along the east face of Laguna Mountains.

Cutting across this older system, a second system trends approximately 45 degrees north of west and is represented by several prominent faults. The most northerly is the San Jacinto, trending west and south of San Jacinto Mountain and extending through Hemet Valley, down Coyote Canyon, and for several miles along the northeast side of Borego Valley. The uplift along this fault has been on the northeastern side and Coyote Mountain, northeast of Borego Valley, is part of a prominent spur elevated along the fault and having a prominent scarp on the southwestern side.

Several faults have been recognized near Warner Valley and extend southeastward in this part of the region; apparently developed by them are a number of so-called valleys, such as Borego, San Felipe, Mason, Vallecito, Collins, and a small one at Banner. Each of these valleys has for its northeastern wall a steep face which is a moderately

battered fault scarp; the south and west sides are much more irregular than the northeast, and the valley slopes are less abrupt. Most of the valleys are high at the southwest, draining to the northeast as though the fault blocks had been tilted to the southwest.

The faults have compelled the streams in most of the valleys after reaching the northeast sides of the valleys to flow southeastward, as is illustrated in Coyote, Grapevine, and Banner Canyons. However, some streams like Banner and San Felipe have eroded deep gorges cutting across the faults, suggesting that the streams were present before the faults were developed and that movement along the fractures was slow enough so that the streams cut downward as rapidly as the rocks were elevated across their paths.

Northeast of the Salton Basin well-defined faults are difficult to make out because of the erosion of the range blocks and the great amount of alluvium which has been spread around their margins. However, topographic evidence suggests very strongly that the ranges have been elevated along fractures. The steep south front of the Cottonwood and Eagle ranges northeast of Highway 60/70 and a prominent scarp at the south side of the Maria Mountains are examples. At the north end of the Palen Mountain east of Desert Center on Highway 60/70, there is definite evidence of faulting.

About 16 miles north of Yuma, Arizona, a long low dam, the Imperial, has been constructed across the Colorado River impounding a large, shallow reservoir. Great canals carry water from the reservoir, one to the California side to supply the Imperial and Coachella Valleys, the other to the southwestern corner of Arizona where there is rich land in the Gila River basin. The California canal has been constructed across the Sand Hills. The main branch gives water to the Imperial section; a smaller one leads north into the Coachella Valley. The desert soils in many places yield splendid crops if water can be supplied. In this highly arid region, the Colorado River is the only sufficient supply. Used since the early part of the century, its water is now being taken in much greater quantity through this All-American Canal system.

The Colorado River forms the eastern boundary of California from slightly southeast of a small settlement in Arizona called Mojave City to the Mexican border. Most of its length in this section is bordered by mountain ranges, the largest on the California side being the Maria, McCoy, Palo Verde, and Chocolate. Depending on the distance of these ranges from the river, its valley ranges from 2 to 25 miles in width. Tributaries are insignificant because of the aridity of the region. The Arroyo Seco, a dry stream channel in the northeastern part of the Imperial Valley is the largest, having a length of about 50 miles. Elsewhere the mountains are connected by alluvial divides which form enclosed basins that do not drain into the Colorado.

Throughout virtually its entire length along the California border, the Colorado Valley is terraced into two parts separated by a prominent bluff 50 to 100 feet high. The lower terrace is that being developed by the river and covered with its sediment when overbank floods occur, the other represents a former level at which the river flowed. The lower terrace, which is called Palo Verde Valley, has a slight slope away from the river because of the formation of natural levees along its banks, the characteristic feature developed especially by a large stream flowing through a lowland region. The surface soil is fine textured, and is added to almost every summer by floods except where artificial levees have been constructed to contain the waters in the normal channel. Numerous old channels and oxbow lakes show the usual wandering of the river from place to place over its flood plain. The Palo Verde Valley in places is 7 to 8 miles wide, but where the mountains come close to the river, as with the Chocolate Mountains near Laguna Dam north of Yuma, it is greatly constricted in width or even absent.

The higher terrace, called the Palo Verde Mesa, is a narrow almost level plain a few miles in width. In some places, the Palo Verde Mesa is broken by bluffs which divide it into a series of terraces standing at various levels. West of Blythe, for example, there is a second terrace 30 or 40 feet higher than the first part of the mesa. The surface of the terrace in most places is sandy or gravelly, but beneath there appears to be finer sediment. However, where good exposures show in the escarpment separating the Palo Verde Mesa from the flood plain below, sand and gravel predominate. Near mountain borders, the terrace rises abruptly and grades into alluvial fans at the mouths of canyons. The surface material in such places is coarse sand, pebbles, and boulders.

The escarpment separating the Palo Verde Mesa from the present flood plain of the Colorado is quite straight and has an abrupt slope, though it has been considerably notched by sheet-flood and flash-flood erosion. On the Arizona side, the terrace bluff is modified by the Gila River which joins the Colorado near the Mexican border. The bluff along the Colorado merges with a similar one which extends up the Gila Valley for at least 50 miles. This would indicate that the escarpments along the two rivers are similar in age and origin.

A particularly notable feature of the bluff on the California side is that it bends westward at Pilot Knob, near the international boundary, passing south of the Sand Hills on the Mexican side, and then turns

northward, merging into the old shore of Lake Cahuila which is marked by a prominent wave-cut cliff for many miles northward.

There is striking similarity between the escarpment along the Colorado River and the escarpments left by the erosion of New and Alamo Rivers as the result of the overflow into the Imperial Valley in 1905 and 1906. For many miles, the gorges cut by these two streams are about 50 feet deep and nearly a quarter of a mile wide. The bluffs along these two channels are similar to those along the Colorado. Also there is such marked similarity between the river bluffs and the old lake shore line east of Imperial Valley that it is impossible to tell where one leaves off and the other begins. The suggestion is strong that both river and lake terraces may have originated at approximately the same time, the explanation possibly being the diversion of the river into the Salton Basin and the formation of ancient Lake Cahuila.

The Colorado River flows down a gently sloping delta plain, whose surface is inclined both toward the Salton Sea and the Gulf of Lower California. The construction of this delta plain of course has been the prime factor in isolating the Salton Basin from the gulf, the delta plain having been built above sea level across the great graben to the Cocopa Mountains on its west side in Mexico. It is well known that at various times the river has discharged into the Salton Basin, which stands as much as 275 feet below sea level. The slope of the delta plain in that direction is greater than toward the gulf, hence, if the river broke through its bank discharging into the basin, its fall would be temporarily increased by 275 feet, and rapid erosion would occur such as happened during the overflow in 1905 and 1906. Furthermore, the basin was then deeper than now by the amount of sediment which was deposited in Lake Cahuila. If the Salton Basin did not fill too rapidly, time might be sufficient for erosion of the Palo Verde Valley to its present depth and width below the Palo Verde Mesa. Climatic fluctuations which unquestionably have affected this entire region during the glacial stages also may have been a factor in the terrace development. There does not seem to be evidence of elevation of the region which would account for the terrace development, hence the two factors mentioned above and possibly others have been involved in their development.

REFERENCES

Brown, J. S., Fault features of the Salton Basin, California: Jour. Geology, vol. 30, pp. 217-226, 1922.

Brown, J. S., The Salton Sea region, California: U. S. Geol. Survey Water-Supply Paper 497, 1923.

MODOC PLATEAU

MODOC PLATEAU

Between the Warner Mountains and the Cascade Range far to the west is a high, semi-arid plateau which is part of the great volcanic field known as the Columbia Plateau that covers a huge area in Washington, Oregon, and southern Idaho. Actually the Warner Mountains and the Hays Canyon Range on the Nevada side were once part of this region, having been elevated into mountains by movements along great faults which broke up that section of the vast tableland in relatively recent geological time. Surprise Valley between the two ranges is a depressed block bounded by faults.

To the California portion of the Columbia Plateau the name Modoc is generally given because it lies very largely within the county of that name, though it is also partly in Siskiyou, Shasta, and Lassen Counties. The elevation of the region averages about 4,500 feet above sea level, but there are many peaks and ridges projecting well above the general level. The main highway crossing the Modoc Plateau is No. 299 leading from Redding to Alturas, and part of No. 89 traverses the southwestern section. A third road, which is oiled, leads from Canby on Highway 299 to Klamath Falls in southern Oregon. There also are a number of dirt roads, mostly of quite uncertain quality, but considerable areas are not reached by road. The geology of the Modoc country is little known, most information relating to that area concerns the vicinity of the Lava Beds National Monument.

The most ancient features in the Modoc Plateau are hills of tuff and lava in the south, southeast, and north. The rocks are dominantly basalt whether flows or fragmental, but interlayered with them are various kinds of water-laid sediments. The hills form wide areas rising from 500 to 1,500 feet above the general plateau level, and they also are present as single prominent blocks surrounded by younger formations in Timber Mountain, Double Head, Indian Butte, and the prominent ridge bounding the west side of Tule Lake basin. Most of the eminences are rounded because of the great proportion of fragmental rocks composing them, and the long time during which they have been subject to weathering and erosion. In places, however, resistant rocks interlayered with the exploded debris form cliffs both above and below which are slopes, thereby evolving a terraced landscape. These volcanic and sedimentary formations quite evidently are part of a once-extensive sequence which has been deeply eroded and also buried by later eruptions. After the volcanic cycle, probably not later than Miocene in age, the region was broken by faults along which there was elevation and depression of blocks. The slope of the layers in the visible remnants shows that the blocks were tilted to some extent in the course of the deformation. Because of the long time which has elapsed since the close of this cycle, the fault scarps have been greatly eroded and

undoubtedly their bases have receded somewhat from the fault zones. The present hill fronts therefore are erosional products of land forms once prominently controlled by faulting.

It is clear that this first volcanic action in the Modoc region was mainly explosive and was related to central openings about which volcanoes were constructed. The activity was interrupted on various occasions and, during the intervals of quiescence, sediments, mainly lake beds, were laid down. Some of these deposits were covered by subsequent outbursts belonging to the same cycle.

The main part of the Modoc Plateau has been built principally in Pleistocene time, the oldest lavas of this sequence being definitely later than those of the deeply eroded Pliocene volcanoes of the adjacent Cascade Range. The youngest flows are so fresh that they cannot have been erupted more than a few centuries ago. These late volcanics are divisible into three groups, the oldest being by far the thickest and most extensive. These lavas were apparently highly liquid, forming thin, rather even surfaced flows, were erupted from fissures rather than from central openings, and flooded the region to build a plain of gently undulating surface. The second group is comprised of generally much rougher surfaced flows, mostly erupted from central vents about which were constructed broad, low shield volcanoes. Explosive eruptions also occurred forming a considerable number of small cinder cones.

The third group includes the most recent flows such as the Callahan on the northern edge of the Medicine Lake Highland, an eastward-projecting promontory of the Cascade Range and the Burnt Lava at the southern margin of the same area. The flow surfaces are chaotic jumbles of great blocks. Rising from their surfaces are cinder cones whose craters and outer slopes are almost perfectly preserved, testifying to the recency of the activity; in fact, this suggests the definite possibility of further eruptions. Evidence given by the volcanics of the Modoc group shows that, as the cycle waned, the eruptions became more and more localized and more explosive.

As the plateau was being formed by the eruption of the Modoc lavas, it was broken by numerous faults. The results of movements along the faults are conspicuously expressed in the landscape. The northern part of the region, especially around the basins of Lower Klamath, Tule, and Clear Lakes, shows a series of fault scarps trending mostly northward. A few, however, are nearly at right angles to this trend. Some of the declivities are low and deeply worn, others are bold, steep cliffs ranging in height from 200 to more than 400 feet. Immediately to the west of Tule Lake basin, fresh scarps are especially well defined. Four of the more prominent ones can be traced for 6 to 12



FIG. 81. Spatter cone on fairly recent basalt flow in Lava Beds National Monument, Modoc County. Cones are formed where concentrations of gas break the crust of an advancing flow and throw clots of lava around the opening. In the background is a cinder cone called Sconchin Butte. *Photo by C. W. Chesterman.*

miles north and south. Three of these scarps face eastward, one to the west. From the top of each cliff the plateau slopes gently to the base of the next one. The gently inclined surfaces of the plateau blocks are quite flat and evidently do not depart far from the original surfaces of the lava flows. The fault-bounded blocks thus have rotated slightly about north-south axes. The boldness of some of the scarps indicates quite recent development.

Rain and snow over the Modoc Plateau are relatively light and many of the lavas are extremely permeable, hence streams and lakes are few and are restricted to the extreme north and extreme south parts of the region, leaving the central section quite destitute of water. The chief rivers are the Pit, McCloud, Fall, and Lost. Old maps show Lost River flowing into the north end of Tule Lake, but apparently the small volume of water which the river carries now is entirely used for irrigation.

Tule Lake, once called Rhett Lake, had an area of about 150 square miles in 1884; by 1924 it had shrunk to half that size, and by 1930 was represented by a small, shallow pond which has since ceased to exist as a permanent feature. Similar recent shrinkage has taken place in Lower Klamath Lake which lies west of Tule Lake. Clear Lake in contrast has been enlarged by construction of an irrigation dam.

Lake sediments are known over considerable sections of the Modoc Plateau which evidently were covered by water in quite late time, possibly during the climax of the fourth glacial stage. Under the Modoc lavas are older lake beds indicating the presence of goodly bodies of water at still earlier times.

It appears that toward the close of the epoch when the oldest volcanic rocks in the region were erupted, probably near the end of the Miocene, north-trending faults developed along which blocks were elevated and depressed. The high areas were vigorously eroded and the debris accumulated in the intervening basins, being mostly deposited in lakes. Later the Modoc lavas were poured out over comparatively level sedimentary plains between the high blocks, eventually overwhelming some of the more deeply eroded residuals and leaving others as the oldest remnants in the existing landscape. In late time further dislocations along north-trending fractures produced the block structure of the present plateau and in the lower-standing areas the modern lakes grew.

The rapid shrinkage of the lakes in recent time is noteworthy. A small amount is the result of development of reclamation projects in adjacent southern Oregon, but most appears to have resulted from climatic change which has caused general decrease in lake size over this region and beyond.

There is, however, another factor which must be considered. Tule Lake has no surface outlet, and, though the basin is nearly dry, there

are no conspicuous salt deposits such as normally are left by evaporating water in so arid a region. Therefore, water not vaporized must be sinking into the ground; this over a considerable period may have enlarged subterranean outlets by weathering and removal of rock, thereby increasing the loss of water.

The Lava Beds National Monument takes in that part of the Modoc Plateau located near the boundary between California and Oregon, partly in Modoc County and partly in Siskiyou County. Comprising about 75 square miles, the Monument is of much historic as well as geologic interest. It was in this area that for half a century the fierce wars between the Modoc Indians and the whites went on. Under Lintpuash, known as Captain Jack, one of the last and bloodiest of the campaigns was fought. With extraordinary skill, this Indian leader and a small band, entrenched in stone forts, the remnants of which may still be seen, and in lava caves, fought a much larger force of white soldiers during 1872-73, until they were finally killed or captured. Mute evidence of the bitter struggle may be seen in many places about the monument today—battle scarred trees, splintered rock, bones of cattle and horses, and the stone forts which gave the beleaguered warriors part of their shelter. Of course it was a losing fight, as eventually were all of the contests between the fewer defenders and the more numerous invaders.

Bearpaw or Bearfoot Cave near the center of the Monument is about 45 miles from Klamath Falls, Oregon, and 65 miles from Alturas, county seat of Modoc County in California. The paved road from Klamath Falls to Canby on California Highway 59 between Redding and Alturas passes a few miles from the Monument's eastern boundary, but the only roads into the area are of dirt and not too good quality, for, although they are in fair condition in places, in others there are numerous lava boulders which make traveling slow and difficult.

At the south end, toward Medicine Lake Highland, the elevation is about 5,200 feet; but this decreases northward to about 4,140 feet at an old shore line of Tule Lake which forms the northern boundary.

The lavas of the Monument, which cover also a much more considerable area in the Modoc Plateau, radiate from faults in the Medicine Lake Highland to the south. One of the best views of the area may be obtained from a slightly eroded cinder cone which lies just beyond the southwest corner. On one side rises Medicine Lake Mountain; northward is a great fanlike flow of dark lava almost free from vegetation. The flow has a blocky top which is extremely rough. Close to the cone are other little explosion volcanoes with craters in their tops; running northward from them are dark, narrow, sinuous trenches. These trenches have been formed by collapse of the roofs of principal lava tunnels and in them are the principal caves and waterholes which played so important a part in the Indian wars.



FIG. 82. Opening of lava tunnel in Lava Beds National Monument, Modoc County. The opening was formed by collapse of a section of the roof. *Photo by C. W. Chesterman.*

Farther north are three long, eastward-facing, parallel cliffs of moderate height, spaced about a mile apart. These are some of the fault scarps referred to in the foregoing description of the Modoc Plateau. At the foot of the eastern cliff is the small remnant of the once great Tule Lake; the cliff, an almost sheer precipice and therefore a quite recent scarp, rises about 1,000 feet; its back is smooth and slopes gently toward the base of the next cliff to the west.

The most conspicuous landmarks in the area are cinder cones rising from 100 to 300 feet above the surface of the flows. The newer ones are little damaged by erosion, the older are somewhat worn; others have been breached by flows that have poured from the vents. In all there are 11 of these little mountains, most of them lying toward the southern side of the Monument.

Less conspicuous are lines of spatter cones or chimneys which mark the location of fissures from which lava quietly poured; they were formed by small foundations of gas-rich lava thrown above the general level of the flow. In many of them are tubes extending downward for 50 feet or more, evolved by the settling of the lava column inside an already hardened wall of rock. Some tubes were developed by gas and lava spatter from holes in the roofs of advancing flows.

Much of the lava has a smooth ropy surface, but some is broken into chaotic jumbles of jagged blocks.

The lava caves and tunnels are found only in the ropy lava, and were formed as the roof and sides solidified leaving a cavity below through which the molten liquid continued to stream. The main tube branches so that, as the flow moved forward, little or no molten lava showed, it having been conducted through a sort of subway from the fissure to the end of the stream. Then through fractures in the sides or front of the flow, the lava escaped leaving the underground passageways. Because the rock jointed as it cooled and contracted, sections of the roofs fell in forming many short caves, hundreds of them being present in the Monument. In length they range from a few feet to

several hundred feet and in height from 10 to 75 feet. The collapsed sections make long, narrow trenches filled with broken rock. Some of the tunnels are divided horizontally so that one lies above another, even though in the same flow. In places the roof has collapsed in such manner as to have sections forming natural bridges.

Bearfoot or Bearpaw Cave in the central part of the Monument has several stories; the approach is a deep trench with almost vertical walls; descent into it is by means of a ladder.

From the roof of many of these tunnels hang lava stalactites, a testimony to the tremendous heat of the liquid stream which was able to melt solid rock. On the floors of a few caves are stalagmites formed by the drip of the molten lava from pendants in the roof.

Because of the high porosity of the lava resulting from abundant joints and other openings, there are no surface streams in the Monument; all of the water goes underground. It is found as pools and as ice, for the temperature in some of these tubes is so low that water remains frozen even during the summer when it is very warm on the surface. In others, the ice melts during the warmer months but the cave temperatures are rarely more than 40°F., and the water is close to the freezing point all of the time. Caldwell Cave in the southeast corner of the Monument is one of the largest showing abundant winter ice which forms on the floor. In summer this is replaced by a pool of water. Crystal Cave, about 2 miles north of the one just mentioned, has great icicles hanging from its roof and ice stalagmites rising from the floor. During the summer the stalagmites and most of the pendants melt but some of the ice remains.

REFERENCES

- Peacock, M. A., The Modoc lava field, north California: *Geog. Review*, vol. 21, pp. 259-275, 1931.
Stearns, H. T., Lava Beds National Monument, California: *Geog. Soc. Philadelphia*, vol. 26, pp. 239-253, 1928.

CASCADE RANGE

CASCADE RANGE

Extending from the north end of the Sierra Nevada virtually to the Canadian border is the Cascade Range which is especially noted for the many great and recently active volcanoes scattered along its entire length. In California, the southernmost conspicuous peak is Lassen which erupted explosively between 1914 and 1917. From this point to Mount Shasta, the range is not particularly well defined though it does contain some cones as large as Crater Mountains (7,418 feet) and Burney Mountain (7,871 feet). Mount Shasta is the supreme peak of the range in the state standing 14,161 feet above sea level, one of the outstanding scenic views in North America. North of this mighty eminence, the Cascade Range is better defined, being composed of a series of giant volcanoes which stand conspicuously above Shasta Valley on the west and Butte Valley on the east. Some of the volcanoes, such as Miller and Eagle Rock, have been considerably eroded whereas others, such as Goosenest and Whaleback, are so young that little change has been wrought in the volcanic form. These peaks rise to heights of 7,000 to 8,500 feet above sea level; the cones made of basalt have broad gentle slopes; those formed of andesite lava are distinctly steeper.

During Pliocene and early Pleistocene times in the southern high Cascades of California and southern Oregon, a north-trending chain of large, gently sloping shield volcanoes was built by outpourings of highly liquid basaltic lava interrupted by a few explosive intervals. The chief of these are Miller Mountain, partly buried under the later lavas of Willow Creek Mountain, and the Goosenest, Ball, and Rocky Mountains, McGavin Peak, and Secret Spring Mountain. East of these along Butte Valley are several contemporaneous shields which have been much modified by faulting.

The cones were simultaneously active and there is no positive indication of the order in which they began to grow. Miller Mountain is the most deeply eroded and may be the oldest whereas flows probably of late Pleistocene age were erupted from Ball Mountain, Ikes Peak, and Eagle Rock Mountain. The craters of all of these volcanoes have been destroyed although relics of former summit cones are on some of them such as Ball Mountain. None of the shields was glaciated, as were Mount Shasta and the great peaks of the Oregon and Washington sections of the Cascade Range, but the margins have been driven back by sapping action of springs and streams which have cut easily into less resistant rocks below the Cascade lavas and therefore have caused breakdown of the margins of the shields.

Most of these volcanoes are elliptical in groundplan and their orientation suggests growth over two sets of faults, one set roughly north-south and the other N30°-45°W.

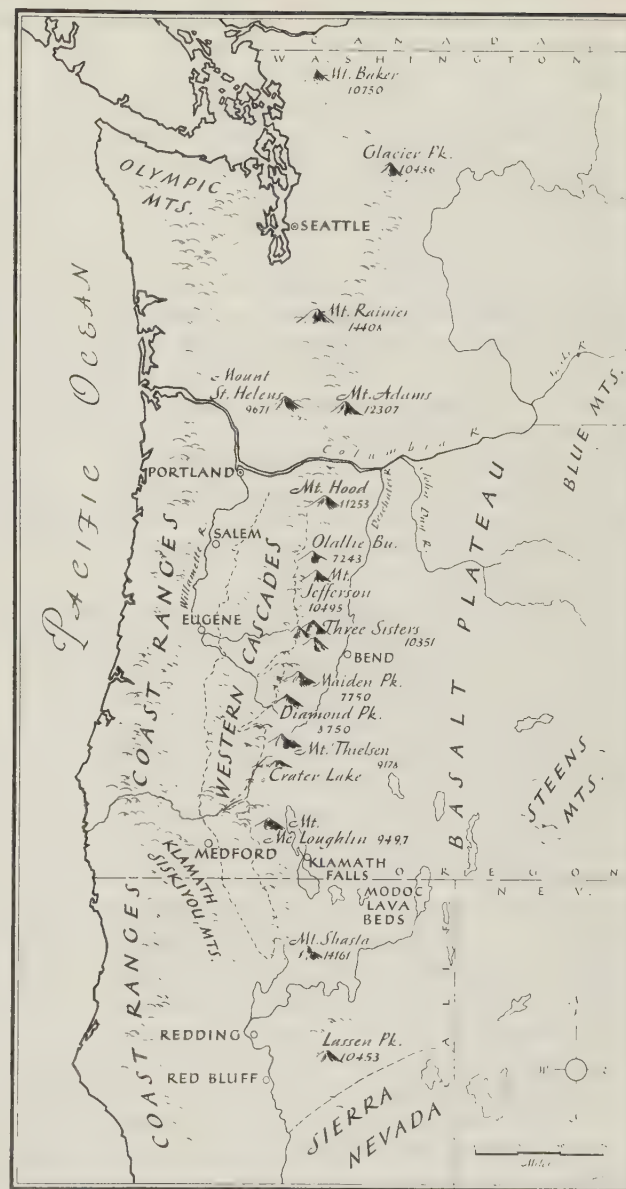


FIG. 83. Map showing distribution of volcanoes in the Cascade Ranges. After Howel Williams.

The eastern shields never extended much beyond their present limits, but the larger western ones must have been much more extensive as remnants of their lavas extend far down the Klamath River Valley and also into Shasta Valley.

Much later than the eruptions just described are those which have occurred since the Shasta glaciers began to retreat as the last glacial stage waned. There are flows and cones, some of which are so fresh that they must have been erupted within the last thousand years or so.

Deer Mountain (7,007 feet), for example, consists of five lava cones built over two nearly north-south-trending faults. Four of the cones are flattish shields of basaltic lava or lava closely approaching basalt in composition. The fifth cone, the summit of the mountain, is steeper. No craters are visible; they have either been destroyed by erosion or filled with later extrusions. Each of the five cones is heavily mantled with basaltic debris blown from nearby vents and all have a thin veneer of the pumice which was blasted from Mount Shasta in 1786.

Near Bolam and Yellow Butte is a considerable area of flows having a distinct hummocky surface which at the southern end is covered by patches of moraines, but farther north has on top only sediment left by subglacial streams. It is believed that these lavas were erupted from fissures near the base of Mount Shasta early in the main retreat of the glaciers on that mountain.

The largest of the late volcanoes north of Mount Shasta is the Whale-back which rises 3,000 to 4,000 feet above the adjacent lowlands. The mountain is a steep cone which has been modified by erosion. At the top there are two mounds of exploded debris; the larger, about 500 feet high, has a well-preserved crater in the top.

Kegg, Soule Butte, and Horsethief Ranch cones are older than the Little Deer Mountain volcano. The first two have been largely destroyed by quarrying, but both evidently were composed of exploded debris. Horsethief Butte is made by two explosion cones whose adjacent sides overlapped as eruptions went on.

Little Deer Mountain is a cinder cone between 500 and 600 feet high breached on the south side. Surrounding it is a field of recent lava more than 10 square miles in area which seems to have been erupted during the waning stages of the volcano.

Perhaps the most conspicuous peak in this part of the Cascade Range is the Goosenest, the top of which rises more than 5,000 feet above the end of its longest flow. The mountain was built on top of a much eroded shield volcano and its slopes are conspicuously steeper than other shields which are adjacent to it. The Goosenest is a large lava cone at the top of which are two cinder cones, the larger being between 600 and 700 feet high, and having a well-preserved crater in the top. The explosive activity had almost ended before any of the visible lavas had been erupted, though buried streams may have been emitted as the outbursts were going on.

Most of the lavas from the Goosenest volcano flowed to the west; the last issued from fissures at the base of the summit cinder cone probably less than a thousand years ago.

The eastern half of Shasta Valley is occupied by a great flow of basalt which has been called Pluto's Cave flow after the large lava tunnel near its southern end. This flow covers more than 50 square miles and exceeds 20 miles in length; it seems to have come from faults close to the northeast base of Mount Shasta. Before eruption of this lava, Shasta Valley was a broad depression containing low hills of andesite some of which still rise as islands above the later basalt. Almost certainly Shasta River and Parks Creek flowed through the valley before being diverted to their present channels by the eruption. The maximum thickness of this immense stream may be close to 500 feet near Pluto's Cave but in Little Shasta Valley it decreases to a few tens of feet.

Toward the head of the flow where it is rather narrow, there is a prominent median ridge and over it there are oval domelike eminences called *schollendomes* formed by the hydrostatic pressure of the lava under the solid crust. In the lower part of the flow there also are pressure ridges and collapse depressions.

The largest of the lava tunnels is Pluto's Cave discovered in 1863 which once could be traced for a mile and a half or two miles. Now probably half a mile is as far as it can be followed, access being easy in places where the roof has collapsed. Most of the accessible part of the tunnel has a diameter of 30 to 50 feet but in places it reaches 80 feet. The floor is heavily covered by blocks which have fallen from the roof and by sand drifted in from dunes on the surface. The walls show that there are three and in places four superimposed flows with clinkery tops and bottoms, which were not separate units, but lobes extruded through the front of the advancing lava.

Oval schollendomes, a few up to 20 feet high, are scattered over the lower part of the flow and marginal pressure ridges, some with gaping fissures in their crests, are common along the eastern margin. Collapse depressions are scattered, but are most numerous near the margins of the lower part. Most were formed by collapse of tube roofs, but some are being produced today by normal weathering processes. In ground-plan they are elongated, circular, or irregular. Many are occupied by ponds and marshes.

In the southern end of Butte Valley is a basalt flow very similar in character to the Pluto Cave stream, and similar basalts probably of the same age are extensively exposed near Bray. All seem to have come from fissures on the east side of the Cascade Range. A narrow flow of black basalt poured from a fissure located about 6,000 feet high on the east wall of Butte Canyon, traveled for about 10 miles, and ended close to Soule Ranch at an elevation of about 4,800 feet. The upper part is almost completely concealed by marshes and meadows

while the lower part is buried by outwash of subglacial streams and by exploded cinders. The best exposures are below Mount Shasta Woods where Butte Creek has eroded a narrow gorge between the eastern side of the flow and a glacial moraine. Most of the lava, which ranges from 10 to 150 feet in thickness, moved through tubes beneath a smooth, undulating crust.

Another flow issued from a fissure near the top of the bold northern wall of Alder Creek canyon, cascaded down this declivity, and continued for about 2 miles, ending with an abrupt front as it spread over the Butte Creek basalt. The surface features are so well preserved that, in spite of the forest upon it, eruptions must have occurred not much over a thousand years ago.

Again within the last one or two thousand years, the Klamath River was blocked by basalt flows forming a lake 35 feet deeper than present Copco Lake at its highest level. The shore lines of this expanded lake are marked by conspicuous benches of diatomite above the present water level. Diatomite is a remarkable rock that contains myriads of the beautiful shells of the minute single-celled plants called diatoms which live abundantly in fresh waters but more prolifically in the ocean. Because the shells are made of silica, a very hard substance, this rock if pure is quarried for use as an abrasive.

The Copco activity began with the eruption of three cinder cones ranging from 200 to 300 feet in height; then flows, at least nine in number, issued from the base of the cones, the longest moving down the valley of the Klamath River for about 2 miles. The flow crusts are blocky, but the lava beneath shows prominent columnar jointing. Most of the columns are vertical, but some are strongly curved like those of the Devil's Postpile in the Sierra Nevada. In part the curved columns developed where younger flows traveled along the channels in the older ones, while others resulted from the intrusion of a later flow into cracks of one already emplaced.

Two recent flows have erupted from the sides of Shasta and Shastina. The older one may be seen a short distance east of Dwinell Reservoir. Along its eastern side it has ridden over glacial moraines, but its surface is barren of glacial features, being mantled only with a thin veneer of cinders. The younger flow, probably the last from Shastina, came from fissures at elevations of 9,000 to 9,500 feet and covered approximately 20 square miles. Highway 95 goes around its margin. Field evidence indicates that the Shasta glaciers had shrunk to about their present size before these lavas were erupted, one flood issuing from the end moraine of Whitney glacier only a short distance below the present front of the ice. These flows are quite perfectly preserved, have very steep fronts, and little forest cover, all testimony of their extreme youth.

From the preceding account it is evident that this remarkable area in comparatively recent time was one of the world's great volcanic

fields. The frequent eruptions must have been magnificent spectacles comparable to those which men have witnessed at many volcanic areas round about the world. The recency of many of the lavas strongly suggests dormancy rather than extinction for parts of the area at least.

Older volcanic features also are present, but are much less spectacular. For example, six volcanic necks which once served as feeders for flows stand close to the Klamath River near Copco Dam, and there are various others in the same area. Some are found in Shasta Valley.

On the eastern side of the Cascade Range and separating it from the Klamath Mountains to the west is Shasta Valley, a roughly oval basin measuring about 30 miles north-south and 15 miles east-west. Most of it stands between 2,400 and 2,800 feet above sea level, hence the Cascade Range rises very conspicuously above it. The eastern half of the valley is occupied by a huge flow recently erupted from the side of Mount Shasta, while the western part consists of older volcanics which have been eroded into a multitude of hills ranging in height from a few feet to 200 and rarely 300 feet. Most of these hills are domes or cones, but some are mesas or ridges. They look much like little cinder cones of fairly recent origin, but actually they are older lavas which have been deeply eroded. Between the hills lie small ponds and marshes and the alluvial flats of winding streams, chief of which are Shasta River and its tributary Parks Creek. In the northern half of Shasta Valley, there are few streams because of the porous character of the lavas and most of the underground water empties into the ponds and meadows of the lower southern end.

On the east side of the Cascade Range is Butte Valley, the bed of an ancient lake, standing approximately 4,200 feet above sea level. Meiss Lake is all that remains of a former much larger body of water that drained through Sam's Neck into the Klamath River. As with Shasta Valley, this depression is a large structural basin, but the faults which bound it are much younger than those margining the western basin. Several flat-floored grabens like Sam's Neck and Pleasant Valley extend beyond the margin of the basin between elevated fault blocks.

When the last glaciers on Mount Shasta reached their maximum about 25,000 or more years ago, those descending its northwest slopes spread into Shasta Valley leaving end moraines along the shores of present Dwinell Reservoir and recessional barriers southward as far as the town of Weed. Today these glaciers have been reduced to a length of about 2 miles and none descend below 10,000 feet. A large glacier starting at about 7,000 feet flowed down the canyons of Alder and Butte Creeks reaching an elevation of about 4,800 feet near Soule Ranch. It overflowed the western rim of the canyon near Granada Ranch, though its thickness was only 400 or 500 feet, and crossed the opposite rim near Mount Shasta Woods, leaving huge lateral moraines. Beyond the ends of the glaciers much outwash was deposited by the streams flowing from them.



FIG. 84. Panoramic sketch of Mount Shasta and vicinity in the California section of the Cascade Ranges. *After Howell Williams.*

Mount Shasta

Mount Shasta is one of the most spectacular of a great galaxy of volcanoes scattered along the Cascade Mountains from Lassen Peak on the south to Mount Baker 500 miles northward in Washington. Shasta is an isolated mountain rising about 10,000 feet above its base and 14,161 feet above sea level. In majesty and beauty it is exceeded among the Cascade volcanoes only by the higher Mount Rainier, prime feature of the National Park of that name in Washington, but others like Hood in Oregon, Baker, St. Helens, and Glacier Peak in Washington are superb structures, standing like great temples above their surroundings.

How old Shasta is we cannot determine, but there are suggestions that the first eruptions began toward the close of Pliocene time. The latest products certainly are not more than a few hundred years old and a hot spring near the summit may indicate that fresh lava still exists beneath the mountain.

Shasta, while not the highest of the Cascade volcanoes, probably is the largest, for it rises from surroundings about 4,500 feet above sea level while Mount Rainier is built on an elevated platform whose surface stands about 8,000 feet above the sea. Some hold that there has been considerable erosion from the top of Rainier, even as much as 2,000 feet of the top being gone, while the summit of Shasta probably has not been lowered more than 200 or 300 feet. Even if removal from Rainier is as great as indicated above, the Shasta cone exceeds it in bulk and height.

Viewed from the east, Shasta appears to be a single mountain, but from other positions it has the form of a double cone, for a small volcano, Shastina, rises boldly from its western side. Shasta, like many volcanic giants similarly constructed, has rather gentle slopes near the base while its upper part becomes increasingly steep. This slope change is caused primarily by the difference in fluidity of the earlier and later lavas; the later lavas being much more sticky when erupted than were the earlier formed shorter, thicker flows which piled up around the central vent making terraces ending in steep, high steps. Furthermore river and glacial action have added their effects, for above 8,000 feet there has been deep erosion while below 5,000 feet

much deposition by streams, gravity streaming, and glaciers has aided in reducing the slope.

Besides the two main cones, there is a line of small cinder cones and plug domes located along a north-south fracture traversing the summit of Shasta and a very prominent plug dome, Black Butte, which rises more than 2,500 feet above the western base of the mountain. Lava flows of rather late date have been erupted along the base of the volcano.

The lower 5,000 feet of Shasta are mantled with thick brush, while between 5,000 and 8,000 feet there is a belt of dense pine and fir forest which gradually merges into the treeless alpine top of the mountain. This alpine section is normally clad with snow from October to June and this greatly enhances the beauty of the peak. Five valley glaciers are fed from as many valley heads in the treeless upper reaches, the largest of these ice tongues being located on the northern side of the mountain where they descend to about 9,000 feet.

Although the main volcano appears to be deeply scarred by erosion, actually it has been marred very little for the deepest canyon, that of Mud Creek, cuts only 1,500 feet into it. Thus a small part of the structure of the cone is visible. That part is composed very largely of lava flows, layers of exploded fragments being relatively few. Of the latter, the most abundant exposures are in the walls of Mud Creek canyon. The last explosions of Shasta came from the summit vent and produced the Red Banks, a deposit of pumice mantling the cirque heads on the south side of the peak.

The crater of the volcano lies beneath a snowfield about 200 yards across. At the margin of the snowfield is a small hot spring.

Evidence indicates that all but the latest blocky lava flows on the northeast side of Shasta and the final deposits of pumice had been erupted when a north-south fracture broke through the summit of the volcano. No displacement of the surface shows along the fissure and little or none may have occurred, but its direction is clearly indicated by the linear arrangement of five plug domes, two cinder cones, and one lava cone. The largest dome is Gray Butte, about 4 miles south of Shasta, which rises about 1,500 feet above its surroundings; the



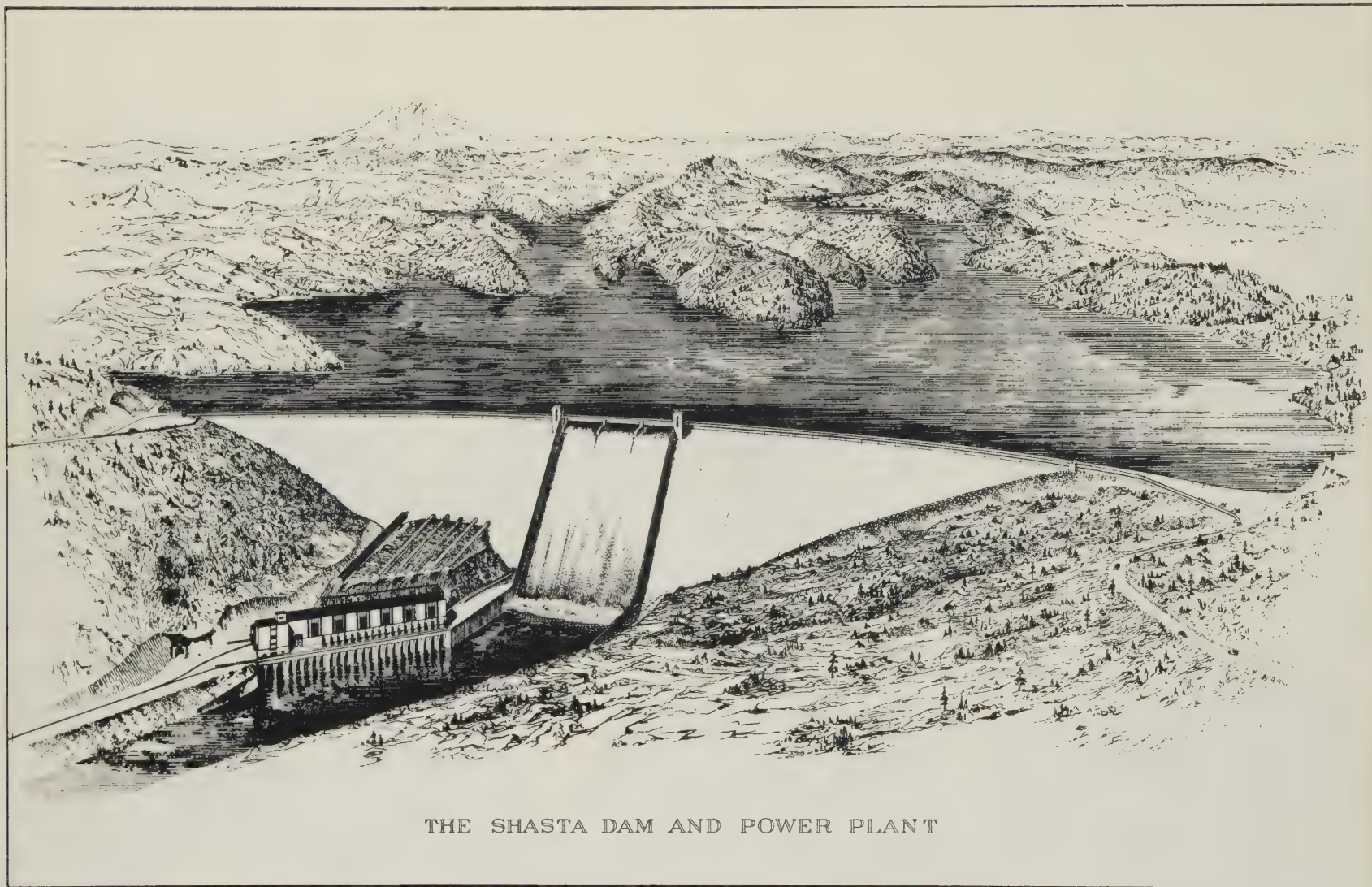
FIG. 85. Mt. Shasta and Shasta Valley. The hills in the foreground are eroded remnants of old lava flows. *Photo courtesy Fairchild Aerial Surveys.*



FIG. 86. Mt. Shasta, a composite volcano composed of two cones. The higher cone, Shasta, is older and has been deeply eroded by streams and glaciers; the lower cone, Shastina, is younger and is less eroded. *Sketched from a photograph by R. N. Wheeler. Norman E. A. Hinds, GEOMORPHOLOGY (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.*



FIG. 87. Mt. Shasta and Shastina, showing the great gash in the crater and side probably caused by explosion. *Photo courtesy U. S. Army Air Corps.*



THE SHASTA DAM AND POWER PLANT

FIG. 88. Sketch of Shasta Dam on the Sacramento River about 16 miles north of Redding. *Courtesy U. S. Bureau of Reclamation.*

length of this dome is nearly 2 miles, but the rock core beneath may not be more than half that, the remainder being the great covering of talus blocks. The cinder cones are small, the northern being only 200 feet high and the southern 800 feet; their summits have been smoothed and the craters destroyed by glacial action. At the south end of the fissure about 2 miles from the town of McCloud is Bear Butte, a small, steep-sided hill composed of dark lava.

A view of Shasta from the west shows a broad low cone rising from its long southern slope. This appears to be a miniature shield volcano of the Hawaiian type, surmounted by remnants of a cinder cone. The lavas composing the main part of this volcano were very liquid when erupted and spread over a wide area even though the slopes they traversed were quite gentle. Most of the flows went southward, though one was partly diverted to the north and changed the course of Panther Creek. Others traveled eastward and encircled Bear Butte, the small lava cone previously described. The longest outpourings from the shield volcano descended the canyon of the Sacramento River for more than 40 miles as long, narrow tongues. The river has cut through the flows, exposing in some places gravels that lay in the bottom of the canyon when the lava invaded and in others the bedrock into which the Sacramento had cut its canyon. Excellent sections of these flows may be seen at Shasta Springs where Mossbrae Falls pours out in great volume much of the underground water coming from Mount Shasta and at other places farther down the canyon. This water is heavily charged with mineral salts.

The main cone of Shasta seems to have attained its present elevation before the large minor cone, Shastina, began to form. It is possible that an east-west fissure developed about the same time as the north-south one earlier described, the two intersecting at the top of the volcano. The first eruptions along this east-west fracture built a small cone about a mile and a half west of the summit of Shasta and somewhat later Shastina began at a second vent a half mile farther west. Until late in its history, Shastina was constructed from short, quite viscous flows which issued from a single vent, but the last principal eruptions came from fissures which opened on the west side of the cone.

The almost perfectly preserved summit crater of Shastina is a bowl-shaped depression about 300 feet deep and half a mile in diameter. Within it are two more or less conical mounds which may be plug domes with much broken tops. In the western side of the crater is a deep breach and below this lies a huge V-shaped gash; possibly both of these features resulted from violent downward directed explosions accompanying the elevation of the domes within the crater, a not uncommon feature at volcanic mountains.

Later explosive eruptions occurred at lower elevations, most of them centering about 3,000 feet below the rim of the Shastina crater, though

activity progressed westward so that some occurred 7,000 feet below or at an elevation of about 5,000 feet above sea level. Dark flows of blocky lava also poured from the fissures covering a considerable area; the longest descended almost to the present site of the town of Weed on Highway 99. These recent flows cannot be more than 200 years old.

Rising conspicuously near Highway 99 not far from the town of Weed is the prominent eminence known as Black Butte whose summit stands about 2,500 feet above its surroundings. From some places the Butte appears to be an almost perfectly conical mountain, but elsewhere this form is seen to be modified by a series of arcuate ridges from 200 to 1,000 feet below the top and located on the northwest side. The diameter of Black Butte is about a mile and a half. The whole of it appears to be made of great blocks of lava which become larger toward the top, only a few crags of coherent rock being visible.

The common belief is that this mountain is a volcano like Cinder Cone of Lassen Park and various others, but actually it is a plug dome very heavily mantled with talus. The core may be cylindrical in form with a diameter of little less than a mile. As the mass rose, cooling and contracting, it was heavily fractured and the great banks of talus formed. Field evidence shows that prior to the protrusion of this dome, explosive eruptions occurred, but whether a small cone was built has not been determined. Black Butte is one of the latest products of Shastan activity and its completion very likely took place in a few years, a striking contrast with the many thousands of years required for the building of Shasta.

Glaciers today cover a very small area on Mount Shasta, about 3 square miles, whereas not far back in Pleistocene time ice apparently blanketed the entire peak. Of the valley glaciers, the Hotlum on the northeastern side is by far the largest, accounting for almost half the total extent of the ice. Bolam and Whitney to the west of Hotlum and Konwakiton on the south side of the mountain are the others. Hotlum glacier descends to an elevation of about 9,000 feet, the lowest point reached by any of the ice tongues; in the early days of exploring Mount Shasta, this ice mass was thought to be about 2,500 feet thick, but now we know that actually it measures only 300 feet which is a maximum for any on the peak. Konwakiton, also known as Mud Creek glacier, has been especially conspicuous at times because of the great mud flows which have descended from it. A few tens of years ago, this glacier was about 5 miles long but since there has been considerable recession. Near its head, the slope of the ice is steep, while farther down, it flattens out, the glacier ending on the brink of a cliff in Mud Creek Canyon. During dry seasons, the run-off from melting snow, which in wetter years is more gradual and sinks into the ground, becomes torrential. Great streams find their way down the crevasses in the ice and emerge on the floor of the valley at the end of the glacier.

The water, carrying large blocks of ice broken from the snout of the glacier, races through a narrow canyon, undermining the weak walls made of tuff and breccia. At times part of the undercut eastern wall collapses into the bottom of the gorge forming temporary dams. Rather quickly sufficient water is impounded behind the barrier either to flow over it or to break through and sweep it on down the canyon. This debris-laden flood after following the canyon for about 6 miles comes out onto flatter land, spills over the banks of the stream, and spreads thick sheets of sand and mud in which are embedded great boulders. Much of the finer detritus is carried into the McCloud River, from there into the Pit, and finally into the Sacramento, at times rendering that stream turbid for 200 miles below the junction with the Pit. These great mud flows were particularly well illustrated during the dry seasons of 1924, 1926, and 1931.

Below Wintun and Hotlum glaciers, other mud flows may be seen, particularly along the banks of Inconstance Creek, but much of the canyons which these tongues follow is cut in lava flows and therefore less debris is available.

Evidence of the fairly late coverage of the entire volcano by ice is provided by the abundance of morainal deposits around the base. However, the glacial history is not well enough known to determine whether there were various stages, though very likely such was the case as may be inferred from their existence farther north in the Cascade Mountains of Oregon, in the nearby Klamath Mountains, and in the Sierra Nevada.

When the glaciers reached their maximum, they descended into Shasta Valley west of the peak, crossed it, and rose to a height of about 4,000 feet along the mountain slopes on the western side. On the southwest, the ice covered Quail Mountain and probably was joined by other glaciers coming eastward from the Klamath Mountains. In the principal valley on the north side of Mount Shasta, the ice was probably at least 1,000 feet thick, while on the south it rose within 100 feet of the top of Red Butte as is proved by polished and striated rock. All but the highest points of Gray Butte were overwhelmed, as were the cinder cones, lava domes, shield volcano, and probably Bear Butte farther south.

Especially fine glacial features are the great cirques on the southwest side of Mount Shasta and some of lesser magnitude on the east. The most perfect of the lot is that at the head of Cascade Gulch between Shasta and Shastina. There are well-preserved moraines in the cirque. Elsewhere high on the mountain good moraines are scarce except at the ends of existing glaciers, but there are some examples on the plateau southwest of Horse Camp. The road to the town of McCloud along the south base of the mountain cuts through a group of side moraines, while in the canyons of Whitney and Bolam Creeks these deposits lie beneath recent flows of blocky lava.

In spite of the abundance of snow and ice on Mount Shasta, there are few large streams and these cease to flow during the winter; most of them are restricted to the north and east sides of the mountain. The cause of the scarcity of water is the porosity of the lavas and the glacial debris. The water sinks below the surface flowing underground to the base of the cone where it comes out in many good sized springs, notably on the south and southwest sides. The finest display is at Mossbrae Falls in the Sacramento Canyon.

Traces of avalanches are numerous especially at elevations of about 8,000 feet where the steep upper slopes gradually flatten out toward the mouths of cirques. Frost wedging apparently dislodges large masses from the highest ridges; in some cases they race over snow-banks increasing in volume as they go. One by the side of the trail up Mount Shasta near Horse Camp, occurring probably not more than 50 or 60 years ago, plowed a path half a mile long through tall timber.



FIG. 89. Flow of basalt that descended the upper part of the Sacramento Canyon for about 40 miles from a vent on the lower, southern slope of Mt. Shasta. The Sacramento River has cut through the flow into much older rocks of the underlying formations. *Photo by Olaf P. Jenkins.*

Pliocene (?) Cascade Volcanoes

Between the Mount Shasta and the Medicine Lake Highland is a broad, irregular mountainous belt whose lavas appear at a few places under the volcanic rocks near the middle of the Highland. Their principal display is an arcuate outcrop around its eastern margin from which they extend westward and merge into the base of Mount Shasta.

This area is composed principally of massive, deeply eroded, grayish, loose-textured lavas, most of which are andesites and basalts which appear to have been erupted from volcanoes of the Shasta type. In fact the character of the rocks and the topography they produce definitely relate them to that sort of volcano, hence they are contrasted with the oldest lavas of the nearby Modoc Plateau which are darker in color and were poured out as fissure flows.

The relief of the area occupied by this belt of gray lavas reaches a maximum of 6,000 feet. Haight Mountain, near the western margin exceeds 8,000 feet; Garner Mountain and Horse Peak each are more than 7,000 feet, Grizzly Peak and several other conspicuous summits stand over 6,000 feet. On the other hand, the Pit River, which crosses the southern part of the area, has cut a gorge below the 2,000-foot mark into the lavas.

Most of the landscape is the product of erosion, being determined by the Pit and McCloud rivers together with their tributaries. However, the major forms seem to be dependent upon original peaks which had been developed during a considerable volcanic cycle. These heights are deeply eroded conical or pyramidal mountains so similar in form to Mount Shasta itself that they are far more likely the eroded products of like volcanoes than dissected remnants of a lava plateau.

The lavas weather easily and have produced a thick soil which supports a heavy forest growth; this results in scarcity of outcrops of fresh rock and makes study of the area a matter of much difficulty.

The volcanoes from which these gray lavas were erupted are believed to have been active in Pliocene time, though the evidence is rather meager.

Medicine Lake Highland

About 35 miles east of Mount Shasta and somewhat to the south of the Lava Beds National Monument is the Medicine Lake Highland, a volcanic center roughly 20 miles in diameter which marks the eastern boundary of the Cascade Range in this section of California. On the north, east, and south, the highland is surrounded by the undulating surface of the Modoc Lava Plateau which in part is broken into small, fault block mountains.

The highland is described as "converging upward to a roughly elliptical rampart of cones and domes," 4 by 6 miles across, on which the highest point is Mount Hoffman, 7,928 feet. This rampart enclosed an elongated basin, the western side of which is occupied by shallow Medicine Lake whose surface stands about 6,500 feet above sea level. The lake has no outlet, but its water is fresh probably because of sufficient seepage into the rocks below to prevent concentration of salts brought into it by feeding streams.

The basement rocks of the highland are basaltic and andesitic lavas like those of the Modoc Plateau immediately adjacent. The growth of the Medicine Lake eminence was started by eruption of rather fluid

andesitic lavas which built a broad shield volcano about 20 miles in diameter. It is believed that the central part of the shield later collapsed forming a basin or *caldera* about 6 miles long and 4 miles in width. As this was going on, more viscous lava was forced up along the fractures forming rim volcanoes. Eruptions continued pouring lava into the caldera until the cones were high enough to discharge flows down the side of the original shield volcano. As a result the fractures were sealed, the walls of the caldera were hidden, and the basin was surrounded by the rampart of cones.



FIG. 90. Panoramic sketch from the top of Medicine Mountain, showing part of the elliptical rampart enclosing Medicine Lake basin. 1, Recent lava flow between Medicine Lake and the northern ridge; 2, Mt. Hoffman; 3, Glass Mountain. After C. A. Anderson.

New vents then opened giving forth sticky, lighter colored lavas of composition similar to or approaching that of granite. The floor of the summit basin is partly covered by a quite recent flow of this type. During this late cycle, more openings were developed on the lower flanks of the old shield volcano, flooding all but the western side with flows of basalt. Many small cinder cones also were formed by mild explosions. On the southeastern side of the shield, a number of cinder cones have coalesced to form a broad ridge. The Modoc Lava Beds are the northernmost expression of the basaltic flows discharged from the fissures along that flank of the Medicine Lake shield volcano.

Recent faulting has developed small scarps and some of the recent volcanic activity has centered along these fractures forming cinder cones and lava cones.

The number of small cinder cones scattered over the highland exceeds a hundred and the latest of them probably have been formed within the last 500 years.

The last basalt flows are very differently distributed for none of them are present in the summit basin or the elliptical rampart surrounding it. All came from vents on the northern, eastern, and southern sides of the shield volcano mostly located between 5,000 and 6,000 feet above sea level. Soils are poorly developed, showing the recency of the eruptions which probably ranged from culmination of the last glacial stage to the last few centuries.

Flows of composition approaching that of granite are limited with exception of those of Little Glass Mountain on the west side to the



FIG. 90a. Mt. Shasta and Shastina. Photo by G. D. Hanna.

center and the rampart of Medicine Lake Highland; some are partly glassy while others are obsidian, the latter representing some of the most recent eruptions in this area. In addition there was considerable explosive eruption of pumice. At both Glass Mountain and Little Glass Mountain, the volcanic cycle was initiated by outbursts of pumice which built up steep sided cones, while later much obsidian was erupted at both volcanoes. Pumice and obsidian also were erupted at still other centers.

Lassen Volcanic National Park

Very close to the southern end of the Cascade Mountains where they adjoin the Sierra Nevada lies a most interesting area which has been set apart as Lassen Volcanic National Park. The best approach is Highway 47 which goes from Red Bluff in the Sacramento Valley to Mineral and Chester and eventually across the Sierra Nevada. At Mineral a road turns north which gives the traveler a splendid view of

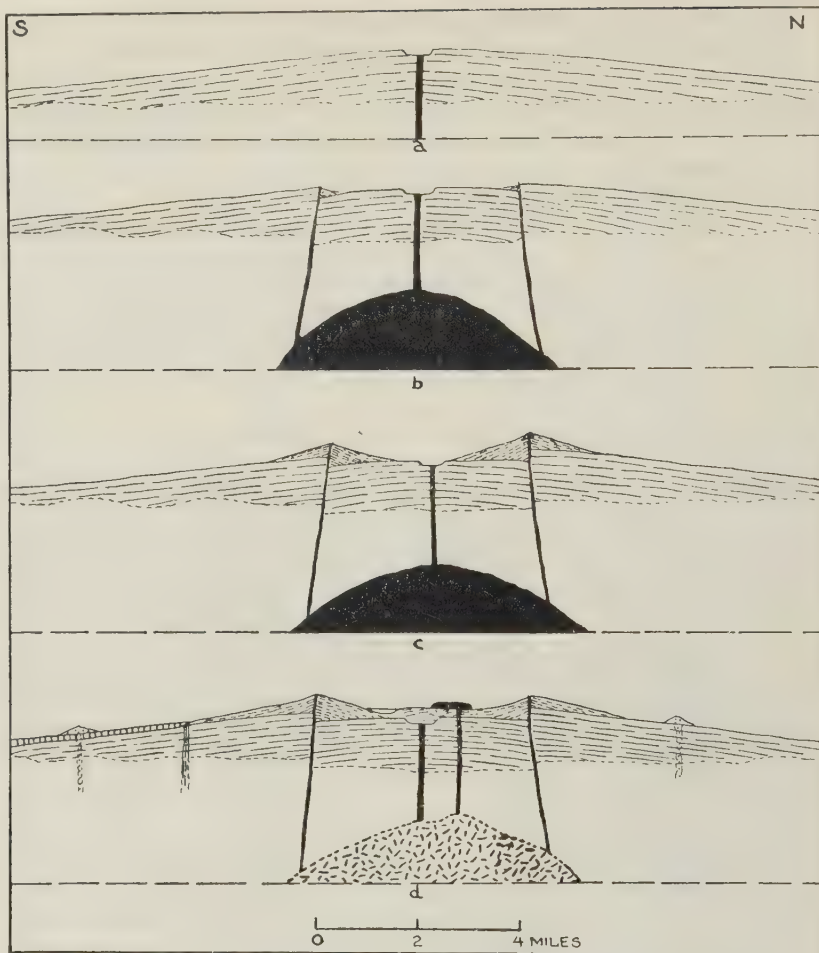


FIG. 91. Cross-section illustrating the origin of Medicine Lake caldera and rim volcanoes. *a*, Shield volcano made of flows of andesite lava. *b*, Collapse of central block along faults. Lava was squeezed up along fractures and poured out on caldera floor. Solid black area is lava chamber. *c*, Continued growth of rim volcanoes discharging lavas down outer slopes of original shield volcano as well as into caldera. *d*, Cross section of present highland showing basaltic cinder cones (stippled) and basalt flows (vertical lines) on outer flanks of shield volcano. Black area in central basin is a recent lava flow. After C. A. Anderson.

the principal scenic features of the Lassen Park. Highway 47 from Redding and 37, taking off from the Redding-Alturas road (No. 299) about 5 miles east of Burney, enter the Park at Manzanita Lake on the north side. Unpaved roads lead from immediately west of Chester and reach sections of the park not accessible by the paved highway; one goes up Warner Valley into a region of hot springs, including the



FIG. 92. Panorama of Little Glass Mountain, Siskiyou County, showing two flows of rhyolite separated by the dark escarpment in central part of photograph. Pressure ridges that developed as flow advanced show on left side. White hill in background is a cinder cone older than the flows. Rocks surrounding flow are older basalt of the Modoc Plateau. *Photo by C. W. Chesterman.*

Geysers, Boiling Lake, and the Devil's Kitchen, centered near Drakesbad, the second passes along the eastern side of Harkness Volcano to Juniper Lake. Features to be seen along the principal highway through Lassen Park are many. This road leads through Mill Valley, across the ancient, much faulted crater of Brokeoff Volcano which is dotted with hot springs. Then, after passing close to the fumaroles (hot gas springs) and boiling springs of Bumpass Hell and glacial lakes Emerald and Helen, it ascends the southeast shoulder of Lassen Peak, where good views of the many volcanic domes, principal features of the Park, and of earlier flows from the original Lassen crater may be obtained. Following the upper part of Kings Creek Valley, the highway goes around the side of bold, talus-mantled White Mountain,

and crosses the valleys of Hat and Lost creeks where the mud-flows of 1915 caused much devastation.

The Lassen region for a long time has been a center of volcanic action, older lavas and explosion products showing at many places. As one phase of this activity, a great volcano was built in the southwest corner of the Park, eventually reaching a height of about 11,000 feet above sea level and a diameter of about 15 miles. Since its completion, this cone has been so much destroyed by faulting and erosion that it is appropriately known as Mount Brokeoff. In the later history of the construction of the Brokeoff Volcano, there also occurred the building of four shield volcanoes of Hawaiian type, one situated at each corner of the Central Plateau of the Park; these are Raker and Prospect

peaks, Red Mountain and Mount Harkness. Each of these mountains is surmounted by well-preserved explosion or cinder cones which rise within the more or less nearly circular fault basins called calderas at the tops of the mountains.

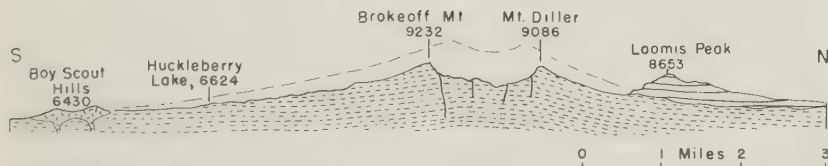


FIG. 93. Section across the Brokeoff Volcano showing by dashed line the approximate original form. Present surface is indicated by solid line. The top of the mountain collapsed along faults, producing caldera in the top. The Boy Scout Hills are plug domes erupted through conduits opened in the lower southern flank of the volcano. *After Howel Williams.*

The eruption of Red Mountain had ceased when an irregular body of rhyolite was intruded into the cone at its northern base. Also after the completion of Raker Peak, a steep-sided dome of lava was protruded through its southern flank. About the same time, a new orifice opened on the northeast slope of the Brokeoff volcano, probably close to if not immediately beneath the present Lassen Peak. From this crater streams of fluid lava flowed radially though principally to the north piling up to a greatest thickness of 1,500 feet. These flows are the black, glassy, beautifully columnar streams that completely encircle the base of Lassen Peak.

Lassen Peak represents a crater filling of the volcano just described. Gas-rich lava had poured out as flows making the mountain just described. Then partly solid, partly liquid gas-poor lava rose to form the Lassen volcanic dome; its sides were abraded as they ground against the walls of the vent and its surface broke apart into blocks which slid down the slopes forming great piles of talus.

Smaller domes rose to the south of Lassen Peak forming Bumpass Mountain, Mount Helen, Eagle Peak, and Vulcan's Castle, and some of these were connected by short, thick flows of evidently sticky lava. Possibly at about the same time the domes forming Morgan and Boy Scout Hills were forced through the southern base of the Brokeoff volcano and that of White Mountain was elevated through vents from which lavas had been poured long before. The domes that border Lost Creek may also belong to this episode. It is evident that all of the domes were rapidly constructed as compared with the much slower building of the older volcanoes from layers of lava and exploded fragments.

This phase of the volcanic action was followed by the collapse of the summit of Mount Brokeoff along a series of nearly vertical faults

producing a caldera having an area of about $2\frac{1}{2}$ square miles. Its origin is similar to that of the Crater Lake Basin in Oregon and many other basins in volcanic mountains. The cause of collapse may have been the large amount of withdrawal of lava from below the area in the formation of the domes above described though very likely underground migration of lava also played a part.

Lassen Peak appears to have risen to about its present height when a vent, Crescent Crater, opened on its northeastern side and erupted flows of lava. Then, about 200 years ago, a line of cones developed at the northwest base of Lassen throwing out clouds of tuff and pumice. Two rather cylindrical domes of highly viscous lava were elevated through these cones to form the Chaos Crag. The latter and northern of the two domes had risen about 1,800 feet when steam explosions burst from its northern base causing that side to collapse and sending a great avalanche of angular blocks over about $2\frac{1}{2}$ square miles immediately adjacent forming the wilderness of boulders called Chaos Jumbles.

In the northeastern part of Lassen Park is Cinder Cone, a finely preserved, very young explosion cone built perhaps about 500 A.D. Not only was the cone formed by the explosions, but the area roundabout, more than 30 square miles in extent, was mantled with the

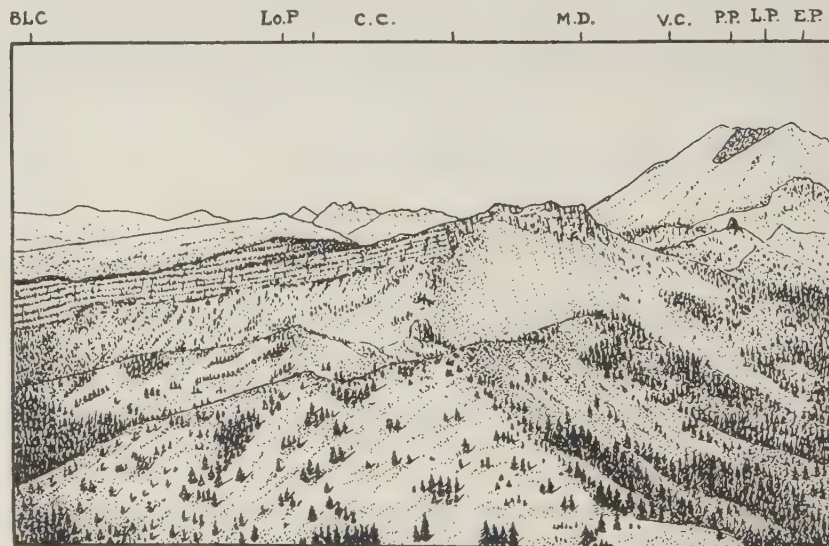


FIG. 94. View north from Brokeoff Mountain across the downfaulted caldera to Mt. Diller (M.D.) and Pilot Pinnacle (P.P.). B.L.C., Blue Lake Canyon; Lo.P., Loomis Peak; C.C., Chaos Crag; V.C., Vulcan's Castle; L.P., Lassen Peak; E.P., Eagle Peak. Dark Tongue on Lassen Peak is the 1915 lava flow. *After Howel Williams.*



FIG. 95. Lassen Peak, Lassen Volcanic National Park, during an artificial eruption, part of the ceremony of dedication of the park. Masses of the solid rock of this huge volcanic dome show through the great banks of talus which mantle its side. *Photo courtesy U. S. Army Air Corps.*

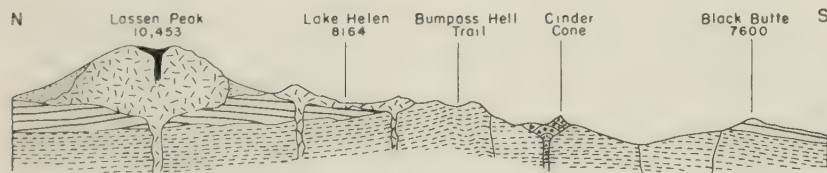


FIG. 96. North-south cross section through Lassen Peak, Lassen Volcanic National Park. After Howel Williams.

debris. Cinder Cone is almost undamaged by erosion and has a perfectly preserved crater in the top. The layered structure of the little mountain, representing the deposits of the various explosions, can be seen in the crater walls. Round about the base are many of the larger fragments hurled from the vent, some of them measuring 4 and 5 feet in diameter. At a later time flows of basalt were erupted from fractures at the base of the mountain, and then these were partly covered by exploded fragments. Finally two very late flows appeared, the second quite reliably dated about 1851.

As late as 1857 steam rose from the domes of Chaos Crags. In May, 1914, Lassen Peak became active, and, for a year, explosions occurred at irregular intervals. In May, 1915, lava rose in the summit crater spilling over the rim on its northeast and northwest sides, melting snow and causing extensive mudflows. On the 22nd of the same month, a horizontally directed blast was loosed from the northeast side of the crater, causing more damage along the headwaters of Hat and Lost Creeks. Afterward the activity became less vigorous and died out in the summer of 1917 with no later recurrence.

The Lassen Dome is by far the largest and highest of these curious but common volcanic features in Lassen Park; it rises about 3,000 feet above its surroundings, standing conspicuously above the smaller domes on its south and northwest sides. The mountain has the form of a truncated pyramid. The steep-sided solid rock core probably measures about a square mile in extent, but enormous masses of talus spread out from it and cover at least twice that much acreage. Especially on the south and east flanks, high rugged crags of the core stand out, but in most places the mantle of debris completely covers it. The great boulder banks were almost entirely developed by the fracturing of the core as it rose, cooled, and contracted, for hot rock shrinks in volume as it cools.

The activity which started in 1914 materially changed the form of the summit crater which before had been a smooth bowl about 360 feet in maximum depth and floored with volcanic sand. No fumaroles (hot gas springs) or other signs of activity were known within the memory of those living nearby. Snow commonly accumulated to depths of at

least 40 feet within the crater. The new volcanic cycle commenced on May 30, 1914, with a short, mild explosion. During the first year more than 150 other outbursts took place enlarging the crater to a diameter of about 1,000 feet. During 1914-15, snow accumulation on Lassen Peak was unusually heavy and this may have been responsible for the activity of 1915 as the meltwater seeped into the earth and came in contact with hot lava. Between May 16 and 18 a mass of black lava rose in the notch in the western part of the crater rim and on the 19th spilled out in the form of a tongue about 1,000 feet long. What happened on the eastern side of the mountain during this time is not clear, but on May 19 a devastating mud flow poured down Hat and Lost Creek valleys carrying 20-ton boulders for a distance of 5 or 6 miles. Three days later a second mud flow occurred in the same place with minor ones of similar sort on the north and west sides of the mountain. At the same time on the eastern side there came a terrific horizontal blast which felled trees for miles around so that their trunks were aligned in the direction of the onrushing cloud of gas and rock fragments. Clouds of steam and ash rose vertically above the crater to a height of more than 5 miles.

Following the vigorous activity of 1915, the energy of the volcano seems to have been largely exhausted. Explosions continued for 2 years at irregular intervals, culminating in violent outbursts of May and June, 1917. There had been considerable snow during the previous winter and this apparently made more underground water available to be turned into steam. After 1917 no eruptions have occurred. The principal effect of the explosions of the last two years was to still further modify the form of the crater. The temperatures generated during the 1914-17 cycle and the type of explosions indicate that Lassen is a waning volcano far on the road to complete extinction.

The volcanic domes called Chaos Crags and the huge avalanche deposit named Chaos Jumbles are the most startling features of Lassen Park outside of Lassen Peak itself. It appears that before the domes were elevated, a north-south fissure probably opened at the northern base of Lassen Peak and explosion cones were built along it. Only part of one cone now shows, but evidence indicates that there were at least two others. The exploded fragments cover a modest area, but bombs and fragments up to 3 feet in length are found at least 3 miles from the cones while abundant bombs 6 feet long are embedded in the deposits 2 miles away. Probably not more than a few weeks or months after the formation of the cones, two great domes were protruded in the cone area. Each was about a mile in diameter at the base and the northern one rose 1,800 feet above its surroundings. Huge banks of talus composed of angular blocks blanket the sides of the domes and many of them are 1,000 feet high. Through the talus and above it rise ragged pinnacles and peaks of more solid rock.

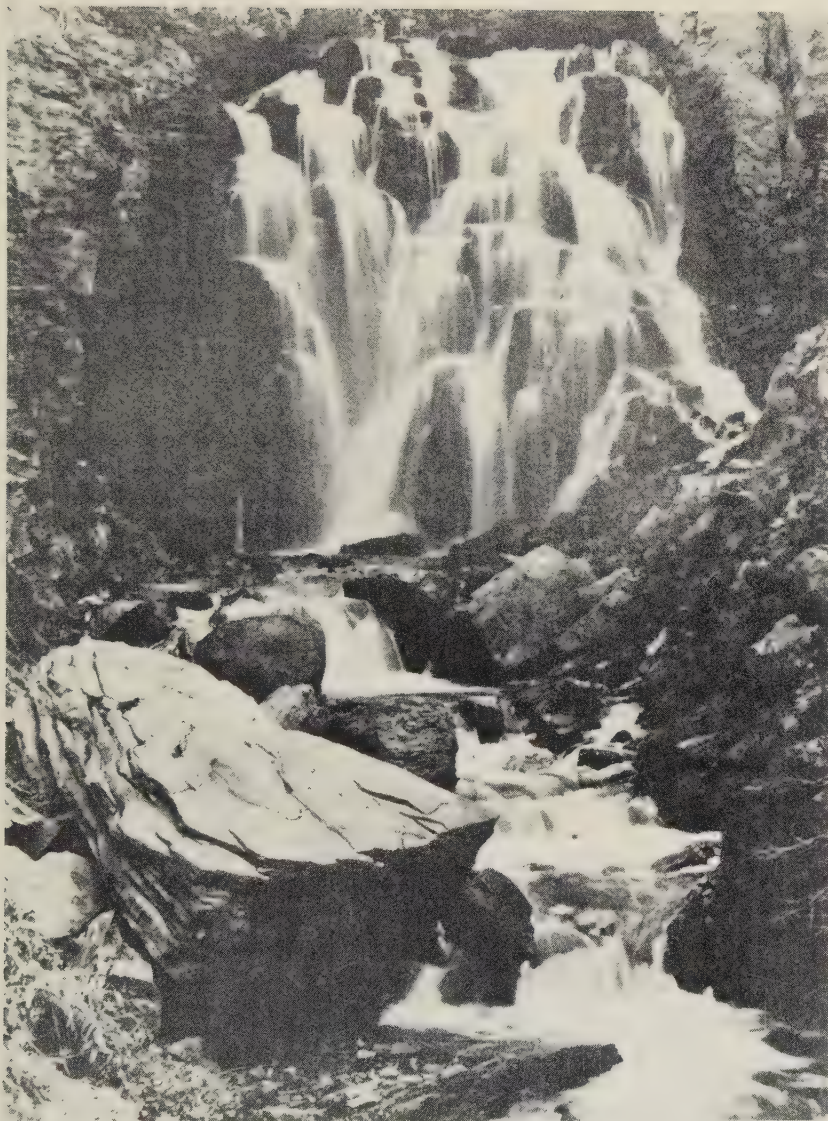


FIG. 97. Kings Falls in Lassen Volcanic National Park. Many lava flows contain open spaces into which water readily sinks. Where valleys are cut into the lava, large, beautiful waterfalls may develop. *Photo courtesy Western Pacific Railroad.*

The later northern dome was made of greatly fractured rock and much of it rested on the loose exploded fragments of the cone beneath, a most perilous setting. Finally explosions occurred at the base of this dome hurling an enormous quantity of huge blocks out to the north. The tremendous speed at which this avalanche traveled can be judged from the fact that its momentum carried the blocks 400 feet up the slope of Table Mountain 2 miles away where Chaos Jumbles ends with a precipitous front. The sharpness of the boundaries of the avalanche mass is notable for almost everywhere its margins are steep mounds, in places more than 100 feet high. It is believed that the blasts which destroyed this part of the dome did not occur more than 200 years ago.

The explosive activity at Cinder Cone in the northeast corner of Lassen Park formed a volcano about half a mile across at the base and 600 feet high. The cone was not formed during a single cycle of activity as are many such mountains, as is proved by the presence of two crater rims, and there are two other rim remnants on the northwest side of the cone. Furthermore remnants of small cones are present on the southwest side of the main mountain. Thus it is evident that activity continued over a considerable period possibly with interruptions of various lengths between the minor cycles. Then followed the eruption of a basaltic lava flow from the south base of the cone and further explosions which partly mantled the flow. Later two or more flows poured out, the youngest of which advanced down a depression in the preceding flows until it spread into the northern end of Butte Lake. This flow is quite reliably dated as having been erupted in 1851. On the surface of these last flows are several small cinder cones.

Hat Creek Valley, which starts about 10 miles northeast of Lassen Peak, extends for about 25 miles to the northwest where it gradually merges into the Modoc Lava Plateau through which the Pit River has cut its canyon. The valley ranges in width from 1 mile to 4 miles. West of it are three prominent volcanic cones, Magee and Burney mountains and Stoney Peak, which rise above a complex of smaller volcanoes, all being part of the Cascade Range which ends south of Lassen Peak.

The eastern margin of Hat Creek Valley is a prominent and only slightly eroded fault scarp, the displacement in part being mostly along a single fracture and in part being distributed along a series of roughly parallel and converging faults bordering step-blocks, each tilted eastward. At the south end of the valley the scarp is about 700 feet high, while 9 miles north it increases to 1,500 feet but this amount of dislocation is distributed along three fault blocks, each bounded by scarps. In contrast with this spectacular topography, there is no evidence that the west side of Hat Creek Valley was formed by faulting. It is true that two faults are present on this side, but the displacement is small and the blocks are downdropped to the west as on the

opposite side of the valley. Hat Creek Valley may be a large block tilted eastward at a gentle angle or a number of smaller blocks similarly tilted and covered by later lava.

In the valley is a large flow of basaltic lava, probably erupted within the last 2,000 years though exact dating is impossible. This flow was discharged from north-south fissures located near Old Station along the highway leading through Lassen Volcanic National Park at the base of Sugarloaf Mountain. This peak is a lava cone capped by a cinder cone, both erupted after the dislocation along the faults above described had been largely completed. At the head of the flow is a series of *spatter* or *dribble* cones ranging from 3 to 30 feet high and having depressions in the top which reach as much as 40 feet in depth. Evidently these cones represent accumulation of lava thrown from a series of lava fountains spaced along fissures from which the magma was being erupted, a feature observed in some recent flows. Tongues of basalt lead from the spatter cones and merge with the main lava stream, showing that the principal source of the magma was that rising along the fractures. These tongues are described as having corrugated surfaces, the small ridges covering lava tubes 1 foot to 2 feet high and 3 to 4 feet wide through which the molten rock moved after a crust had formed above.

Some of the lava from the spatter cones flowed westward surrounding several older basaltic cones, but most traveled northward joining the main part of the flow near Old Station. The flow near Old Station swept eastward from the source vents, then north down Hat Creek Valley for a distance of about 16 mile.

Lava tubes are common throughout the flow but most are small. The best known and one to which travelers through the park often go,



FIG. 98. Chaos Craggs, Lassen Volcanic National Park. In the foreground is part of the Chaos Jumbles. Photo by T. H. Eastman.

called Subway Cave, is about a mile northeast of Old Station. It has a height of 12 to 15 feet and can be followed for a distance of half a mile. Collapse of joint blocks from the rock has made possible entrance to the tube.

The lava is much jointed and these fractures together with the numerous tubes make the flow highly pervious to water. Hat Creek is the only stream which flows continually over the flow. On the east side of the valley a stream coming from the plateau flows northward for a distance of 5 miles before disappearing into the pervious lava. At the lower end of the flow, the water table is close to the surface of the lava so that pools of water fill depressions in its surface and these gradually merge into a stream, Rising River.

REFERENCES

- Anderson, C. A., Volcanic history of Glass Mountain, northern California: *Am. Jour. Sci.*, vol. 26, pp. 485-506, 1933.
- Anderson, C. A., Volcanoes of the Medicine Lake Highland, California: *Univ. California Dept. Geol. Sci. Bull.*, vol. 25, pp. 347-422, 1941.
- Williams, Howel, A Recent volcanic eruption near Lassen Park, California: *Univ. California Dept. Geol. Sci. Bull.*, vol. 17, pp. 241-263, 1928.
- Williams, Howel, The history and character of volcanic domes: *Univ. California Dept. Geol. Sci. Bull.*, vol. 21, pp. 51-146, 1932.
- Williams, Howel, Geology of the Lassen Volcanic National Park, California: *Univ. California Dept. Geol. Sci. Bull.*, vol. 21, pp. 195-385, 1932.
- Williams, Howel, Mount Shasta, a Cascade volcano: *Jour. Geol.*, vol. 40, pp. 417-429, 1932.
- Williams, Howel, Geology of the Macdoel quadrangle, California: *California Div. Mines Bull.* 151, 1949.



FIG. 99. Raker Peak, Lassen Volcanic National Park. Left side of the peak is plug dome; right side is a lava cone capped by a cinder cone. In the foreground is part of the 1915 mud flow. After Howel Williams.

KLAMATH MOUNTAINS

KLAMATH MOUNTAINS

The Klamath Mountains include a rugged though not particularly high region lying west of the Cascade Mountains, south of the Oregon Coast Ranges, and north of the California Coast Ranges, being divided between the southwestern part of Oregon and the northwestern part of California. Many local names are applied to various ranges such as Siskiyou, Klamath, Marble, Scott Bar, Trinity Alps, and others, but in the ensuing description the term Klamath is applied to the entire area. Within the California section there are many magnificent scenic areas, both along the coast and within the mountains themselves. Much of the coast is boldly cliffed, the canyons are deep and narrow in most places, and the peaks and ridges rise boldly above. The higher mountains have been glaciated giving them particularly bold contours and in these areas are beautiful rock basin lakes. Fortunately the Klamath country has not been so extensively penetrated by roads as have some other mountainous sections of the state so that the primitive character of the region is largely preserved. Some of the high points are Condrey Mountain (7,116 feet), Red Mountain (8,317 feet), China Mountain (8,551 feet) and Russian Peak (8,163 feet) in Siskiyou County; Thompson Peak (8,936 feet), Caibour Mountain (8,563 feet) and Gibson Peak (8,378 feet) in Trinity County; and South Yolla Bolly (8,083 feet) in Tehama County.

The principal drainage system is the Klamath River which starts east of the mountains in the Modoc Plateau and Cascade Range, eventually flowing into the ocean about 15 miles south of Crescent City or 30 miles south of the Oregon border. At the settlement of Weitchpec between 30 and 35 miles from its mouth, the Klamath is joined by its principal tributary the Trinity, the South Fork of which flows for a long distance through a great structural depression whose origin has not yet been worked out. Some other minor streams drain west into the Pacific and some eastward into the Sacramento River which has its source in a small lake on the eastern side of the Klamath region. The Sacramento River, together with the Pit and McCloud Rivers, which flow through the area, are the principal drainage lines in the eastern part of the Klamath Mountains. The picture has been altered somewhat by the construction of Shasta Dam located on the Sacramento River a short distance below its junction with the Pit. This giant concrete barrier, principal element in the great Central Valley Project for flood control, irrigation, and other purposes, impounds a large reservoir extending up the canyons of the Sacramento, the Pit, and the McCloud. The last two rivers now enter this large artificial lake.

Geologically the Klamath Mountains are sharply contrasted with the bordering ranges, for they are comprised largely of pre-Paleozoic

and Paleozoic sedimentary rocks, volcanic rocks, and many intrusive bodies. Along the eastern side Triassic and Jurassic strata are exposed and the intrusive masses may be partly or largely Mesozoic. The Klamath formations have been greatly deformed and many of them considerably metamorphosed. In contrast, the California section of the Cascade Range is comprised largely of Cenozoic volcanics while the California Coast Ranges consist almost entirely of Mesozoic and



FIG. 100. Emerald and Sapphire Lakes, Trinity Alps. The two lakes occupy rock basins excavated by a glacier. Photo by Eastman Studio.



FIG. 101. Castle Crags, a stock of granitoid rock intruded about 130 million years ago and uncovered by erosion. Mt. Shasta is in the background. *Photo courtesy U. S. Army Air Corps.*

Cenozoic sediments and volcanics, with the oldest Mesozoic formations belonging to the late part of the Jurassic period. The great bulk of Coast Range formations are Cretaceous and Cenozoic. On the southwest side of the Klamath Mountains, the natural boundary with the Coast Ranges would appear to be the South Fork of the Trinity River, but the South Fork Range on its southwest side is comprised of Klamath formations and therefore must be included in that province.

The Klamath Mountains are sharply distinguished also from the Coast Ranges in the character of their drainage systems. Fold-faulting of the Klamath area probably occurred in the late Jurassic when the Sierra Nevada and various other California ranges were created. The Coast Ranges are infant mountains now in process of development by fold-faulting which started in very late Pliocene and Pleistocene time. In the Klamath region, because of erosion which has gone on since Jurassic time, control of drainage by folded and faulted features evolved when the mountains first appeared has long since been wiped out, hence the streams do not follow structural trends. In the Coast Ranges, on the other hand, folded and faulted ridges, troughs, and basins are conspicuous, and the streams to a notable extent are directed by them.

The Klamath Mountains lie in the path of the moisture laden winds which sweep eastward from the Pacific. Along the coast rather equable climate prevails, though the extremes are greater than in the Coast Range belt and farther south.

Precipitation along the coast is moderately heavy, averaging 39 inches annually at both Eureka and Crescent City, a few miles north. Within the mountains at Monumental (2,550 feet) there is an astonishing increase to 109.4 inches, but at other stations at the same or even higher elevations, the figures are much lower ranging between 28 and 52 inches with the higher figures at higher elevations. Measurements are made at so few places that a very incomplete picture of precipitation over the Klamath area is available. Undoubtedly over the higher ridges particularly in the western part precipitation approaches or may exceed that at Monumental. Along the eastern base of the mountains there is sharp decrease, with annual averages of 17 to 26 inches at three stations, Hornbrook, Yreka, and Edgewood whose elevations range from 2,154 to 2,933 feet. At equivalent elevations somewhat farther west, average annual precipitation ranges between 36 and 52 inches. Snowfall in the winter months in places is heavy reaching a measured maximum of 126 inches at Monumental and 108 inches at Gilta (3,300 feet), 60 miles to the southwest. At Yreka on the eastern border, the annual average decreases to 16 inches.

The abundance of rain and snow gives many permanent streams through the region though there is material fluctuation in their volume because of the heavy concentration of precipitation during the winter months.

When viewed from higher peaks or ridges, the ruggedness of the region so impressive from canyon bottoms or in climbing the steep slopes in a measure departs, for most of the ridge tops have considerable similarity in elevation which increases from the coast inland and from south to north. By imagining the canyons to be filled in, one gains the impression of a former advanced landscape characterized by broad valleys separated by ridges of moderate height. Near the coast the elevation of the ridge tops ranges from 1,700 to 2,500 feet increasing to 4,500 feet 50 miles inland; in places, as in the South Fork, Salmon, and Yolla Bolly Mountains, the elevation increases to 6,000 or 7,000 feet. The ancient landscape evidently was warped and probably faulted during elevation and has been very deeply dissected by the invigorated streams.

Above the general level made by most of the ridges certain residual peaks rise for 1,000 to 5,000 feet and lower ones from 100 to 600 feet in height are common. Some of the higher areas undoubtedly represent erosion remnants but others may have reached their present position because of movements along faults. Among the highest sections in the California part of the Klamath Mountains are the Siskiyou Mountains between the Klamath and Rogue river basins, the Scott, Salmon, and Trinity Mountains which make the headward parts of divides between three large forks of the Klamath River flowing into it from the northeast.

The Bullychoop Mountains in Shasta County marks the divide between the Trinity and the Sacramento rivers and the Yolla Bolly Mountains between the Sacramento and the streams of the California Coast Ranges.

When the oldest and highest erosion surface was being developed at an elevation much lower than its remnants now possess, the streams ran transverse to the dominant structural trends of the region just as they do now. Apparently the Jurassic mountains had been sufficiently worn down so that the control of stream direction by folded and faulted ridges and depressions and other parallel structures had been largely wiped out. This surface must have been evolved by Miocene or early Pliocene time. Since then there have been various rejuvenations with streams returning to youth, later advancing to maturity and developing terraces below the level of the oldest landscape. Various terrace levels have been recognized, but they do not represent so continuous a landscape as that represented by the high level remnants. In late Pliocene and Pleistocene time, the principal uplift of the Klamath region occurred and with it the great amount of erosion which has evolved the rugged landscape of today.

In the higher mountains moderate ice attack occurred during the glacial stages, both from permanent ice fields and from true glaciers. The usual cirques, U-shaped valleys, hanging valleys, rocks basins, and moraines are present, though on a relatively limited scale. The



FIG. 102. Klamath Mountains near Weaverville. *Photo by J. H. Eastman.*

history and extent of the glaciation has not been worked out, but it definitely was no match for that in the Sierra Nevada.

One of the best known sections of the Klamath Mountains is the Castle Crags west of Dunsmuir. The ragged spires and pinnacles have been eroded into a much jointed stock of gray granitoid rock which was probably intruded at the time of the Jurassic folding which built the first mountains in this region. The stock has been exposed by the deep erosion which has followed the fold-faulting of this distant time. Another much more scenic area is the Trinity Alps, one of the highest and most rugged parts of this province, located about 15 miles north of Weaverville. The peaks and valleys in part have been moderately glaciated and consequently their contours are bolder than the average for the region. A number of beautiful little lakes lie high up in the deep, narrow canyons.

In a number of places in the Klamath Mountains such as near Weaverville and Hyampom there are basins containing moderate thicknesses of sediments and some volcanic rocks principally of Eocene age. These deposits are notable, as Tertiary sediments are rare in the entire province. Probably the basins have been evolved by faulting which very likely occurred after the deposits were laid down, protecting them from extensive erosion.

At various places along the coast there are elevated shore features—battered wave-cut cliffs, erosion and deposition terraces and eminences

that once were islands. One terrace has been reported at an elevation of 1,500 feet, another prominent one at least a mile wide in places at 1,000 feet, and a third at 500 feet. There are others less sharply defined. Unfortunately studies of the coast line in this part of California go back many years and future investigations undoubtedly will alter the picture we now have of the uplift and erosion that produced these features. Whether the highest standing surfaces mentioned above actually are marine terraces remains to be confirmed; that there are some at lower elevations is certain. Prominent cliffs with the usual attendant features are now being eroded along most of the coast in the Klamath region giving a bold shore landscape which in places is magnificent.

A notable man-made feature is the huge, three-pronged artificial lake impounded behind the huge Shasta dam which has been constructed on the upper Sacramento River near the site of the former copper smelting and mining town of Kennet some 16 miles north of the city of Redding. This immense concrete barrier is 560 feet high and 3,500 feet long across the crest. When the water is in the reservoir the vast lake is a beautiful sight, but when it falls there is an ugly strip along the shore littered with sediment and dead vegetation. The reservoir is part of the giant Central Valley Project, a combined flood control, water supply, and power generating system which will be of growing importance to the Great Valley as agriculture and industry of that region develop.

Oiled road access to the Klamath Mountains is limited and even dirt roads are none too numerous. Highway 101 runs along the coast and 299 leads from Eureka, principal city of the northern California coast, to Redding at the north end of the Sacramento Valley. A branch taking off at Willow Creek goes into Hoopa Valley. Highway 199 leaves 101 at Crescent City and crosses the northwest part of California's Klamath Mountains on its way to Grants Pass in Oregon. An oiled road follows the Klamath River for many miles, and another also branching from Highway 99 goes to Etna. On the eastern side Highway 99 traverses the Klamath Mountains from the Oregon border to their junction with the Sacramento Valley. By bridge this highway twice crosses the immense reservoir behind Shasta Dam.

REFERENCES

Diller, J. S., Tertiary revolution in the topography of the Pacific Coast: U. S. Geol. Survey Fourteenth Annual Report, 1892.

Diller, J. S., Topographic development of the Klamath Mountains: U. S. Geol. Survey Bull. 196, 1902.

GREAT VALLEY

GREAT VALLEY

Almost completely enclosed by mountains is one of the most notable structural depressions in the world, the Great Valley of California more than 400 miles long and averaging 50 miles in width. Most of the valley lies close to sea level in elevation, but along the margins in places it rises somewhat higher, the maximum being about 1,700 feet at the tops of steep alluvial fan slopes which rest against the mountains at the southern end. Most of the eastern boundary is not much more than 500 feet high but the western is lower, ranging from 50 to 350 feet along the greater part. The basin has a single outlet, Carquinez Strait, crossing a section of the Coast Ranges through which the Sacramento River flows into San Francisco Bay. In the part of the Sacramento Valley near Carquinez Strait there is considerable land standing below sea level now protected from flooding by natural levees and artificial dikes.

Bordering the Great Valley are the Tehachapi, Sierra Nevada, Cascade, Coast and Klamath Mountain Ranges. The basin has existed for a long time; record of it is found from the folding which elevated the Sierra Nevada, the Klamath, and other California mountains in the late part of Jurassic time. During the Cretaceous period and much of the Cenozoic era, the basin extended over most of the area now occupied by the Coast Ranges and had its western margin along the base of the old land, Cascadia, which has since disappeared. At times, such as in the late Jurassic and Cretaceous periods, the lowland was under water. In the land now occupied by the Coast Ranges local deformations and volcanic activity altered the topography of different sections, particularly during the Cenozoic era, and in the present valley area there were oscillations above and below sea level. Late in the Pliocene epoch the compression forming the Coast Ranges started and continued throughout the Pleistocene generating a fold-fault mountain system of moderate height. The elevation of this mountainous belt materially narrowed the width of the basin, developing the present outline of the western margin late in geological time. Into the Great Valley flowed the drainage from the surrounding mountains, most of the water coming from the Sierra Nevada, the Cascade and Klamath Mountains. These streams have deposited immense quantities of sediment forming a great flood plain with alluvial fans around the mountain base. Most of the streams joined two trunk rivers, the Sacramento in the north and the San Joaquin to the south. The Kings River which enters the Great Valley from the Sierra Nevada south of the San Joaquin has formed a huge alluvial fan that projects across the valley, joining one formed by a Coast Range stream, Los Gatos Creek, shutting off the part of the valley to the south as an interior basin. Formerly this section was occupied by shallow lakes,

but most of the water has been drained to increase agricultural area. The largest of the lakes was called Tulare which gave its name to the basin, though actually the area contained others as well.

Sacramento Valley

The term Sacramento Valley commonly is used for most of the low country through which the Sacramento River flows. However, there is a considerable range of low hills north of Red Bluff developed in a broad anticline that separates the section still farther north from the much larger stretch to the south. This northern division includes a number of minor valleys which deserve separate names.

The Sacramento River has its source in a small lake on Mount Eddy, one of the peaks of the Klamath Mountains, about 50 miles south of the northern boundary of California. After flowing eastward for about 12 miles, it turns to the south for 370 miles to the head of Suisun Bay, 50 miles northeast of San Francisco, where it unites with the San Joaquin River. North of Redding the Sacramento was joined by the Pit River which flows from Goose Lake on the east side of the Warner Mountains in Modoc County across the great stretch of lava beds into which it has cut a deep, narrow gorge. A few miles east of its junction with the Sacramento, the Pit received the waters of the McCloud River which comes from the Mount Shasta section of the Cascade Mountains. Many other tributaries are added farther south, mostly coming from the Sierra Nevada.

The main part of the Sacramento Valley is about 150 miles long. Its greatest width is about 40 miles and its elevations range from slightly below sea level to about 300 feet above in the main section.

Most of the surface is quite flat and monotonous, a product of the long time during which sediment has been deposited in this great trough. In places, some folding and faulting have occurred, raising these sections above the general level and making it possible for streams to develop hilly or gently rolling topography quite sharply contrasted with the normal landscape. In the middle of the valley, quite discordant with its even contour, are the prominent Marysville or Sutter Buttes. The two principal eminences, North Butte and South Butte, are 1,863 and 2,132 feet respectively above sea level, the highest points in the entire basin.

Five natural divisions are recognized in the Sacramento Valley—the *red lands* standing more or less conspicuously above the present flood plain which is comprised of *low plains*, *river lands*, *flood basins*, and *islands*.

Red Lands. The red lands are belts of hilly or gently undulating country found in places along both sides of the Sacramento River, and generally sloping toward the axis of the valley. These areas once were almost as even surfaced as the lower parts of the valley today, having

been constructed by the various streams coming from adjacent mountains and representing a flood plain and alluvial fan level higher than the present one. Later this plain was deformed by gentle folding or faulting which made it possible for the streams that built them to erode instead of deposit.

In the northern part of the Sacramento Valley, the red lands extend almost to the middle of the valley and the Sacramento River flows through a wide, shallow trench bordered by discontinuous bluffs which it has eroded through them. On the east side of the river, the red lands are narrow and not sharply separated from the low plains in the vicinity of Red Bluff, but farther south their width and definiteness increase until at Vina they are about 4 miles wide and are separated from the low plains by bluffs about 50 feet high. In this section they are cut by streams coming from the Cascade Mountains which have eroded narrow, terraced valleys. South of Vina, the red lands are lower and disappear before reaching Chico.

West of the Sacramento River, the border of the red lands is a conspicuous bluff which extends from Red Bluff southward to Tehama; while south of that city to the Glenn County line, the boundary is poorly defined with more or less detached hills and knobs extending down to the river.

From Chico southward to the Yuba River, the red lands occupy a considerable area on each side of the deep, terraced gorge of the Feather River. From Chico southward and from the Yuba River northward, the red lands increase from scattered higher patches surrounded by the low plains to wider and wider tracts of highland, until on each side of the Feather River they form broad bench lands standing from 325 to 425 feet above sea level. In the region south of the Yuba River, east of the Feather River and the American basin, the red lands are only slightly elevated above the present level of the streams. They rise gradually to an elevation of 100 to 300 feet but merge into the low plains so that a definite boundary cannot be drawn between the two.

On the west side of the Sacramento River, the red lands are less extensive than on the east, but are much more sharply defined, because uplift has made a sharper break between them and the low plains and because the soil in the low plain is yellowish. This color difference is not so conspicuous on the east side of the Sacramento River, as the reddish color of the upland areas is not strongly developed. The reddish color has been produced by oxidation of iron molecules contained in the sediment. From Stony Creek south to Williams, the red lands occupy small areas flanking the foothills of the Coast Ranges and rise about 100 to 200 feet above the streams flowing through them. Their much dissected surface slopes abruptly from the foothills to the low plains. Between Willows and Williams the red lands increase in width and ruggedness.

The most extensive area on the west side of the Sacramento River runs from Williams southeastward to Cache Creek. The southern part is called the Hungry Hollow Hills but this term is applied by some to the whole area. This section is a plateau 100 to 450 feet above sea level, bounded on the northeast by a remarkably straight and uniform though somewhat eroded fault scarp. The southern part has been greatly dissected into hill-valley landscape, but farther north there are remnants of the flat-topped plateau.

South of Cache Creek, but offset to the west, is another tract of red lands also apparently bounded by a fault scarp, which fringes the foothills increasing in width until near Winters it is a half mile to 2 miles across.

On the north end of the narrow throat through which the San Joaquin and Sacramento Rivers find their way to Suisun Bay are the Montezuma Hills, circular in groundplan and about 12 miles in diameter with their west side joining somewhat detached foothills of the Coast Ranges. This is a much eroded remnant of red lands sloping from elevations of 250 to 300 feet above sea level on the southwest to only 25 feet on the northeast where it merges with the surface of the low plains and of the Yolo Basin. On the south and southwest, the Montezuma Hills are bounded by sharp bluffs rising above the Sacramento River or above narrow plains bordering the salt marshes of Suisun Bay.

River Terraces. Streams tributary to the Sacramento River have terraced valleys in the edges of the foothills and in the red lands. The terraces vary in width and height in different valleys, but in a given valley, they are constant in their relative position above the stream; they generally are detached remnants along the valley sides. There are two principal terrace levels, the upper level being 20 to 50 feet below the general surface of the red lands, the lower 10 to 20 feet below that and 5 to 20 feet above the flood plains now in process of development.

Only streams rising in the mountains and crossing the valley border have terraces. Their history indicates three stages of valley cutting, widening, and filling with sediment, the last being now in process. Causes of the evolution of the terraces include intermittent uplift with consequent limited downcutting by the streams until their downcutting power became so small that they began to widen the valleys producing erosion terraces later covered with flood sediment. The known climatic changes of the Pleistocene also may have played a part. The history of the region is not sufficiently well known to determine the factors involved.

Low Plains. The low plains lie between the red lands and the river lands, but where the red lands are absent they stretch to the base of the mountains. They stand somewhat lower than the red lands and their surface is almost level. The plains have been built by the streams

coming from the mountains which have eroded the red lands and the evenness of their surface results from sedimentation which is still going on. They are the highest portion of the flood deposits being formed by the streams.

The low plains are comprised partly of alluvial fan and partly of ordinary flood plain deposits. The fans are characteristic of the mouths of intermittent streams which have carried large quantities of debris from the mountains, depositing very rapidly as they emerge from canyon mouths. The two most notable examples are the fans of Stony and Chico Creeks, both broad and rather gently sloping. In some places closely spaced fans have coalesced into alluvial aprons as at the foot of Hungry Hollow Hills in the vicinity of Arbuckle.

On the west side of the Sacramento Valley from Williams south to the Montezuma Hills, intermittent streams issuing from the hills carrying fine sediment have developed raised banks on either side which are natural levees rather than fans; they stand from 3 to 20 feet above the bottoms of the channels and range in width on each side of the channel from 500 yards to 3 miles depending on the size of the stream which has produced them.

The streams forming these levees not only build up their banks but also deposit silt in their channels, thus raising their level and lowering the slope over which they flow. Bed and banks together lowering gain in elevation forming inconspicuous double crested ridges standing 10 to 25 feet above the lowland on either side. They show principally at time of flood since the lower adjacent areas are under water while the long sinuous ridges stand above. Not infrequently flood waters burst through a levee starting a new channel with banks built up along it similar to the old, leaving abandoned channels below the point of diversion and giving a series of forking ridges. The levees along these intermittent streams are similar in character to those along the permanent rivers like the Sacramento, but are much smaller.

Toward the sides of the Sacramento Valley the low plains merge into and are represented by the more actively forming flood plains of tributary rivers, which are of two types—those of permanent and those of intermittent streams.

In the first group are the flood plains of the Mokelumne, the Cosumnes, and the American Rivers, which are a half mile to 2 miles wide and rise from a few feet to 20 feet above the rivers. Through the plains the rivers run with sinuous but not strongly meandering courses. Human activities have so changed conditions along the Bear and Yuba Rivers that they no longer have their original appearance.

River Lands. The river lands are quite narrow belts rising 5 to 20 feet above adjacent land and extending along both sides of the two principal streams in this portion of the valley, the Sacramento and the Feather. They are natural levees which have very gentle slopes toward

the flood basins or adjacent low plains, and have been built in recent time by overflow from the rivers. The levees do not stand very high above their surroundings, but their elevation is enough to make them habitable, their soil arable, and thus to separate them from the swampy and frequently submerged lands through which they run for many miles.

Flood Basins. On both sides of the Sacramento River between the natural levees or river lands and the low plains are broad, shallow basins locally known as *tules* because of the heavy growth of tules or rushes which they formerly supported. There are five principal basins—Butte, Colusa, Sutter, American, Yolo, and two smaller ones—Marysville and Sacramento.

These areas are dry most of the year or sometimes for whole seasons, but, during major floods, they are inundated forming shallow lakes. Before reclamation had been undertaken along the river, about 60 percent of the valley was subject to overflow, including the basins, the river lands, and a considerable portion of the low plains.

The flood basins are broad, shallow troughs filled during floods by the side streams which sweep across the low plains in broad sheets and by rivers discharging into them through definite channels, or overtopping the natural levees and the river lands. Deposition in the basins comes primarily from standing rather than from running water, hence their surfaces are almost ideally even, though there is a gentle slope toward the center and the downstream end of the basin. The soils are heavy, less satisfactory for ordinary agriculture, but successfully used for growing of rice.

Islands. At Clarksburg, minor channels break away from the Sacramento River, flowing for a distance, then joining other channels or the main river. These many channels therefore are interconnected and also are connected with similar channels of the San Joaquin River. Both the Sacramento and the San Joaquin enter Suisun Bay by separate courses in a gap about 4 miles wide between the Montezuma Hills and the Diablo section of the Coast Ranges. On account of the various channels above the river mouths part of the discharge of the Sacramento may enter Suisun Bay through the San Joaquin River and vice versa.

Between the channels are islands bounded by natural levees formed by these minor branches of the Sacramento and therefore basin shaped. Under natural conditions the islands were partly covered with water during much of the year and were almost completely overwhelmed during high floods. The tide raised and lowered the level of water over large areas, thus helping to scour out and keep open the minor channels. The natural levees therefore are composed of silt and loam deposited during the overflow while the central part of the islands contain peaty material formed from decaying vegetation which grew in them when covered by water. Artificial levees have been built on top of the



FIG. 103. Dike along San Joaquin River. Woodland Island in foreground. Material used to build dike was obtained by dredging the river. *Photo by Mary Rae Hill.*

natural preventing the flooding of former years. Rainwater and seepage from the river are drained by a canal cut through the central flat of each island leading to its lower part, and pumping stations are maintained to lift the water over the river banks. During the dry season, water is pumped from the river for irrigation and the surplus runs to the lowest end of the island where it is pumped back into the river.

Marysville or Sutter Buttes

Rising conspicuously above the almost level floor of the Sacramento Valley about 20 miles northwest of the city of Marysville are the Marysville Buttes or as they are locally known the Sutter Buttes. Occupying an almost circular area about 10 miles in diameter, their highest point stands 2,132 feet above sea level and almost that amount above the surrounding lowland. In any view from a distance two distinct features stand out—peripheral slopes extending in a long, gentle curve to a height of 600 or 700 feet and the abrupt and ragged peaks and domes making the central part of the mass. With almost featureless plains extending for miles round about, the buttes make a startling landmark visible for long distances.



FIG. 104. Victoria Island in San Joaquin River. Asparagus fields in background. *Photo by Mary Rae Hill.*

The Marysville Buttes are a volcanic mass, principally a laccolithic intrusion which is a roughly mushroom-shaped body of small size that deformed the covering strata into an anticlinal dome as it was being emplaced below the surface. During and after the intrusion of the igneous mass, the overlying layers were largely stripped away. Then steam explosions developed a central crater by blasting through the core of the laccolith and constructed a volcanic cone. Other minor volcanic eruptions also occurred.

Prior to the intrusion of the laccolith, the present site of the buttes seems to have been a plain like the rest of the Sacramento Valley and

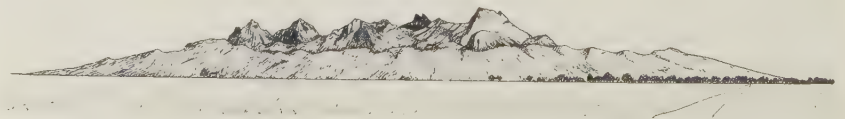


FIG. 105. View of Marysville (Sutter) Buttes from near Williams, 20 miles west. South Butte is high peak on right; West Butte is central peak. *After Howell Williams.*

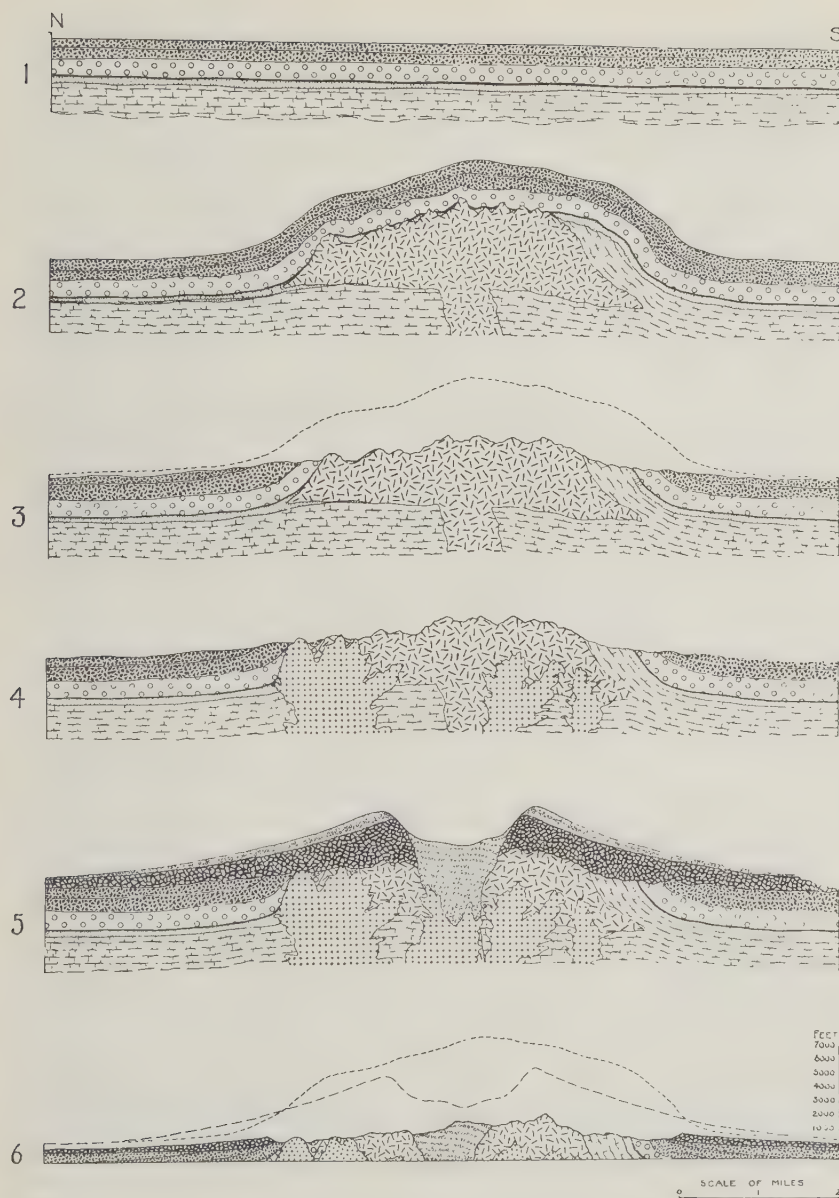


FIG. 106. Stages in the development of Marysville (Sutter) Buttes. 1, Original structure of sediments under Sacramento Valley. 2, Intrusion of laccolith and doming of sediments. 3, Erosion of the sedimentary cover and laccolith. 4, Intrusion of rhyolite domes. 5, Further intrusion of rhyolite and explosions forming volcanic cone over eroded surface of laccolith, domes, and sedimentary ring left from erosion of original cover of laccolith. 6, Production of existing topography by erosion. After Howel Williams.

was underlain by nearly flat-lying sediments such as are being laid down in many places today by the streams which flow through the valley. The rise of the magma was forceful enough to arch the strata above it until the cover could yield no further to this type of deformation; it then was broken apart by a series of faults part of which are radial to and part concentric with the margin of the laccolith. The blocks thus produced were tilted outward at various angles.

The intrusive body apparently has steep sides toward the top and flattens out irregularly near the margins. The top of the body was covered by an uneven blanket of sediments; how much rock has been eroded from the blanket and intrusion is uncertain but evidence rather strongly indicates that the tops of the buttes are not far below the original surface of the body. Also how high a dome was originally produced cannot be determined because the roof was being eroded while deformation was proceeding under the impetus of the rising magma. Field evidence indicates that when the later volcanic explosions occurred, the sedimentary cover had been stripped off about as it is today, showing that it has only recently been denuded of the cover of volcanic debris imposed upon it.

Following emplacement of the laccolith but before most of the explosive eruptions occurred, necks or stocks of rhyolitic composition were intruded both into the margin laccolith and the surrounding sediments.

When the sedimentary cover had been largely removed from the laccolith, violent steam explosions evolved a central crater and minor craters near the margins. No fresh magma was erupted, the products being fragments of previously consolidated rocks erupted at relatively low temperatures. The first outbursts were vigorous, indicating long accumulation of gas pressure under the mountain, but the intensity decreased and intervals between the various explosive cycles were long enough to permit deep erosion of debris which had been previously blasted out. This would indicate that magma, still being intruded at depth, was crystallizing and expelling gas which accumulated until the explosions began.

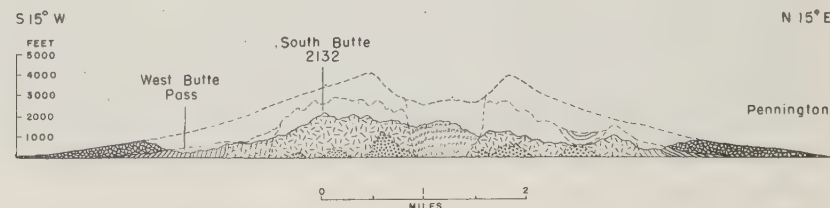


FIG. 107. Generalized section across the Marysville (Sutter) Buttes showing by solid line the present topography, by the lower dashed line the surface of the laccolith believed to have been stripped of its sedimentary cover before the explosive cycle started, and by the upper dashed line the possible form of the principal cone built by explosions. After Howel Williams.

Before the explosive phase commenced, the mountain was a more or less cone-shaped eminence with high points standing about 3,000 feet above sea level. The explosions opened a roughly cylindrical vent in the central part of the laccolith which is now filled with the products of the last eruptions. The violence of the eruptions varied, for some threw out angular boulders up to 15 feet long while others emitted only fine-textured debris.

The more forceful outbursts erupted great masses of coarse as well as fine fragments which apparently swept down the sides of the cones in avalanche fashion. When the eruptions were less intense, the products were finer and formed well-bedded deposits which contrast with the chaotic nature of the avalanche debris. Also there are other deposits formed by streams which flowed down the slopes of the volcano both during the explosive phases and episodes of quiescence. The cone which was formed above the laccolith probably had an elevation of about 5,000 feet.

Besides the major eruptions, there were many minor ones from the principal crater and from smaller openings along and near the margins of the laccolith. The explosions of the subsidiary vents doubtless built small cones.

The final explosive products are fine tuffs which seem to have filled the crater of the volcano; in some exposures they are more than 1,000 feet thick. From their field relations it appears that they were erupted from a long, narrow fissure located near a crescentic valley in the southwestern crater wall.

For a time, the volcanic cone must have been an imposing edifice in this very flat region, but now most of it has been removed so that the resistant rock of the laccolith now makes up the principal mass of the buttes.

San Joaquin Valley

The larger part of the Great Valley, extending southward from the Cosumnes River and Suisun Bay is called the San Joaquin Valley, although its entire area is not drained by the San Joaquin River and its tributaries. The southern, more arid third, extending from the Kings River to the base of the Tehachapi Mountains, has no surface outlet under normal conditions, and the surface waters accumulate in Tulare Lake and Buena Vista Reservoir. Tulare Lake formerly received a portion of the excess flow of the Kern River, but by means of a restraining dike, water is kept out except when floods break through. The original lake bottom has been converted principally to wheat-growing land.

The streams draining from the Sierra Nevada bring practically all of the water reaching the San Joaquin Valley, hence their volume is many times greater than that of streams coming from the other bordering highlands and their flow is much less erratic.

This strong dominance of drainage from the eastern side has given the valley an unsymmetrical form, for the axis or line of lowest elevation is much closer to the Coast Ranges than to the Sierra Nevada. In places the axis even lies along the base of the western ranges, but in other localities the western slopes may reach half the width of the eastern as between Los Gatos and Cantua creeks. The slopes of the western side are somewhat steeper than those of the eastern.

This unsymmetrical cross section, which in most places is not characteristic of the Sacramento section, results from the greater aridity of climate. The streams, overloaded with sediment because of decreasing volume as they reach the lower, drier mountain slopes have formed conspicuous alluvial fans, the larger, of course, growing at the mouths of the eastern streams.

Over the fans the streams discharge in numerous channels flowing from the apex at the mouth of the canyon in different directions down the slope. Most of these *distributaries* as they are called travel outward on the sediment of the fan into which they have cut fairly deep trenches, but some from the San Joaquin River northward have eroded into the bed rock below the fan to a depth not exceeding 100 feet, the result either of recent elevation of the Sierra block or change in stream volume, the actual cause not yet being known.

The west side fans, particularly near the middle and southern parts, are steep and symmetrical, features characteristic of areas of slight rainfall quite unevenly distributed where the streams are smaller and have greater fluctuations in volume. The eastern fans, on the other hand, are much larger, more gently sloping, and less clearly defined.

On the eastern side the Kern River fan has grown westward against the McKittrick Hills isolating the Buena Vista basin south of it. Originally shallow Buena Vista Lake occupied part of the basin and during unusually rainy seasons there was overflow northward into Tulare Lake. Later on dams were built changing the natural conditions, impounding the waters of Buena Vista reservoir. Northward, the effect of aridity has been expressed by the building of the great Kings River fan which has joined one from Los Gatos Creek flowing from the Coast Ranges forming a low ridge behind which is the Tulare basin. Part of the water from the streams south of the barrier was impounded to form Tulare Lake which, when present, was very shallow. Because of this and the fluctuating water supply, the lake varied notably in extent from year to year.

North of Tulare basin, discharge from the streams is great and constant enough to prevent formation of such dams and an open channel is maintained by the San Joaquin River to Suisun Bay. The trunk river meanders sluggishly through its flood plain.

Along the lower course of the San Joaquin, the topographic picture in general is similar to that along the Sacramento as it is developed



FIG. 108. Meanders of the San Joaquin along its flood plain. *Photo courtesy Fairchild Aerial Surveys.*

under somewhat more humid conditions. Large areas along the river are annually inundated by flood waters except where protected by artificial additions to the natural levees. The major floods occur when both the San Joaquin and the Sacramento are in flood at the same time. North of the mouth of the Stanislaus River, 20 miles south of Stockton, numerous channels diverge from the San Joaquin as from the Sacramento, isolating islands similar in topography to those already described.

The great contrast between the two major sections of the Great Valley is found in the southern, arid San Joaquin portion where the surface is a combination of alluvial fan surfaces with intervening shallow basins of the *playa type*, the Tulare and the Buena Vista. Farther north and throughout the Sacramento section, fans are less striking because of the greater amount of rainfall, and although they are present along the valley margins, the main feature of the valley is the flood plain.

The Kettleman Hills lie close to the eastern base of the California Coast Ranges about 10 miles southeast of Coalinga in the San Joaquin Valley. They form a slightly arcuate low range having a northwesterly trend, a length of about 30 miles, and an average width of 4 to 5 miles. The hills rise rather abruptly several hundred feet above the San Joaquin Valley to the east and are separated from the Coast Ranges by the almost flat Kettleman Plain which is 3 to 5 miles wide. The greatest elevation of 1,366 feet above sea level is at the northern end, from which there is a decrease southward until the hills merge almost imperceptibly with the even surface of the San Joaquin Valley. The Kettleman Hills are the main part of the isolated outermost foothills of the Coast Ranges which extend southeastward from the mountain front along the axis of the large Coalinga anticline. Three major anticlines comprise the Kettleman Hills, named respectively North, Middle, and South domes; they have echelon alignment and are offset. North and Middle domes are doubly plunging anticlines, that is their axes are inclined in two directions whereas South Dome plunges northwestward and is overlapped on the south by the alluvium of the San Joaquin Valley. The whole line of folds of which the Kettleman Hills are a part extends from Anticline Ridge to Lost Hills, a distance of about 70 miles.

South and Middle domes are separated by Avenal Gap, an alluvium-floored depression extending from the Kettleman Plain to the San Joaquin Valley. No similar feature lies between North and Middle domes, the boundary between them being marked by decrease in ruggedness and change in trend. North Dome is the highest of the three and is most deeply eroded. Its culminating point, La Cima, stands about 600 feet above the Kettleman Plain and 900 feet above the San Joaquin Valley.

The Kettleman Hills have been developed by deformation of a surface of very low relief which had been etched into sedimentary beds of Cenozoic age and apparently extended far beyond the limits of the area. The deformation is believed to have resulted from renewed folding along the already existing Coalinga anticlinal belt. The erosion surface elevated by the deformation has been largely destroyed within the area of the hills. The domes contain two concentric rows of hills separated by shallow valleys excavated in weaker strata, an *escarpment-cuesta* topography common in such structural settings. The crests of the hills in some places may represent parts of the old surface somewhat modified by erosion. One nearly flat remnant of the surface about a mile long and a quarter of a mile wide shows near El Prado at the north end of the Kettleman Hills, and other smaller remnants are present elsewhere. A lower erosion surface evidently formed by trenching of the older surface and broadening of the new valleys shows in some places. The deformation which gently folded and elevated this erosion landscape certainly occurred during Pleistocene time and probably rather late in the epoch.

The entire Kettleman Hills area is characterized by rounded hills, but, in most of North Dome and on the west side of Middle Dome, the lower parts of the stream valleys are relatively narrow and steep sided. Locally the hill slopes are gullied into badlands, since the weak rocks are insufficiently protected by vegetation from the attack of torrential rains. The drainage is all intermittent, but, when it flows, transports enough sediment to add to alluvial fans which have formed at the mouths of the gorges where they open onto the adjacent plains. The headwater streams of North Dome have relatively deep, narrow valleys, but the lower parts of some of them have reached maturity, are widening their valleys, and are depositing sediment over the terraces they have cut.

Small patches of sand dunes are found here and there. In the San Joaquin Valley immediately adjacent to the Kettleman Hills, there are long northwestward-trending ridges of sandy material which some have suggested as eminences resulting from recent faulting but which actually may be old sand dunes of considerable size modified by later erosion.

REFERENCES

- Bryan, Kirk, Geology and water resources of the Sacramento Valley, California : U. S. Geol. Survey Water-Supply Paper 495, 1923.
- Mendenhall, W. C., and others, Ground water in San Joaquin Valley, California : U. S. Geol. Survey Water-Supply Paper 398, 1916.
- Woodring, W. P., and others, Geology of the Kettleman Hills oil field, California : U. S. Geol. Survey Prof. Paper 195, 1940.

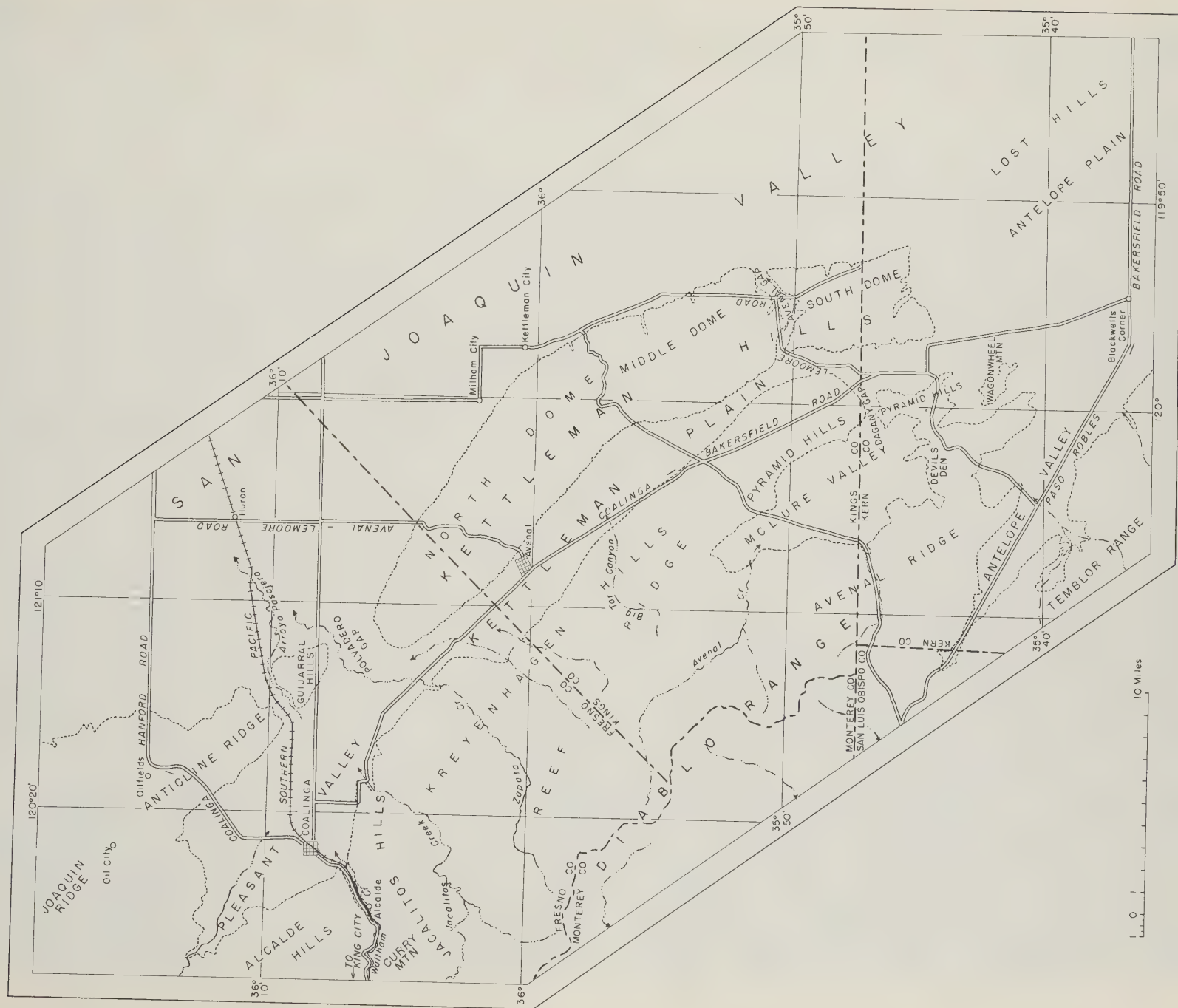


Fig. 109. Map of part of west side of San Joaquin Valley. After U. S. Geological Survey.



FIG. 110. Kettleman Hills, anticlinal domes in the southwestern part of the San Joaquin Valley. *Photo courtesy Fairchild Aerial Surveys.*

COAST RANGES

COAST RANGES

The California Coast Ranges form a physical province about 400 miles long and 50 miles wide between the Pacific Ocean and Great Valley. They are composed chiefly of late Jurassic and younger formations, and their topography is controlled by folds and faults. The province contrasts sharply with the older Klamath Mountains to the north. The Coast Ranges adjoin the Transverse Ranges to the south, the San Rafael Mountains being the southernmost coast range. The Coast Ranges in most places rise abruptly from the shore line, their western margin being marked by prominent sea cliffs. On the eastern side, the break between the mountains and the Great Valley is generally rather abrupt.

Along the coast the climate of the Coast Ranges is controlled by the the moisture laden winds sweeping on shore from the Pacific Ocean. The temperature variations between day and night are normally small, summers are cool, winters moderately warm, and there is considerable fog. From south to north in the province, temperature variations increase, there is greater contrast between summer and winter, fog is more frequent and lasts longer, and rainfall increases. Snowfall is uncommon at low elevations except in the far northern part but the mountains, especially from San Francisco north, receive not infrequent snow.

The part of the Coast Ranges that is best known extends from the San Francisco Bay region to Santa Barbara County. The first deciphered chapter of the history begins with the formation of a comparatively small geosyncline lying between the ancestral Jurassic Mountains, particularly the Klamath, Sierra Nevada, and Transverse Range sections, and a land mass called Cascadia, which lay west of the present shore line. During the latest part of the Jurassic and most of the Cretaceous periods, dominantly elastic sediment was deposited in the basin, the debris being derived principally from the western land. There were interruptions when the land rose above sea level, especially at the end of Cretaceous time when there was some folding and faulting. Throughout the Cenozoic down to the last epoch the basin oscillated above and below sea level, though the influxes of the ocean were not so extensive as in the two preceding periods; in addition the land was less stable as shown by folding and faulting and by the products of volcanic activity. When above the ocean the relief of much of the Coast Range belt was similar to that of the Great Valley today, with which it was then coextensive.

In the middle part of the Miocene epoch, compressive deformation began and gradually became stronger causing part of the Coast Range region to rise as ridges above sea level while other parts remained below and received sedimentary deposits. How much of the belt became land to be eroded we do not yet know. The rather weak compressive

movements continued at intervals through the earlier part of the Pliocene epoch and became very much intensified in the later part of that time when the entire Coast Range belt seems to have been strongly folded and faulted, with the deformation being strongest near the coast and less pronounced eastward. A still more important deformation of similar type started in the middle Pleistocene, stamping the general features of the present landscape on the Coast Ranges and establishing the main features of the drainage. Subsequent changes along the coast and inland seem to have been of less significance. The formation of the Coast Ranges therefore has been a complex process spread over a considerable interval from the middle part of Miocene time to the middle of the Pleistocene, the compression increasing in severity and reaching its climax in the last deformation. Movements since the middle Pleistocene apparently have been predominantly vertical, either upward or downward.

The mid-Pleistocene folding accentuated Pliocene folds and faults and formed new structures of the same sort which deformed strata laid down both below sea level and above during later Pliocene and early Pleistocene time.

The mid-Pleistocene uplift was rather rapid, greatly steepening the mountain fronts from which great and small masses of slide rock broke loose. That these slides occurred some time back is proved by the amount many of them have been eroded. At numerous places there are hills and ridges along the mountain fronts that are covered with slide debris derived from the scarp of the principal ridge behind the bordering hills. In some localities there is a sequence of slides with the later being smaller because of decrease in the slope of the mountains as erosion gradually subdued them. These huge jumbles of rock in many places completely hide the scarps, giving an erroneous impression of the distribution of the rock formations and structures.

Along the coast and in the valleys there are many finely developed marine and river terraces shown to be later in origin than the mid-Pleistocene deformation because they commonly transgress structures formed at that time. The terraces testify to the spasmodic character of the uplift of the various blocks, having been evolved during episodes of quiescence and raised during times of increased intensity of deformation. In certain places there may be definite intervals between terraces, but farther along these intervals change, indicating difference in rate of uplift which warped the terraces as they rose above the sea.

Coastal terraces do not seem to correspond very closely with those developed along river valleys within the ranges, probably the result of more rapid uplift along the west side of the province since middle Pleistocene time than has occurred farther east.



SPENCE
Air Photos

FIG. 111. Coast Ranges from the south end of the Cuyama River. Valleys paralleling the trend of the range are principally depressions evolved by folding, faulting, or both; gorges in the ridges are produced by sheet floods, flash floods, and streams. *Photo courtesy Spence Air Photos.*



FIG. 112. Culiente Range, east side of Cuyama Valley in San Luis Obispo County. Alluvial apron formed by the coalescence of steeply sloping alluvial fans borders the base of the mountains. *Photo courtesy Spence Air Photos.*



FIG. 113. Elevated wave-cut terrace at Point Arena. *Photo by Olaf P. Jenkins.*



FIG. 114. Tilted strata north of Pescadero Creek. Sea cliff and elevated terrace in background. *Photo by Olaf P. Jenkins.*

The best known and perhaps the most important fault or rift system in the Coast Ranges is the San Andreas. In the central portion of the province where this great fracture zone has been most thoroughly studied, it lies close to but not exactly along the course of a different type of fault formed in Eocene time. What the relationships are in other places we do not know, except that in places it does transgress faults and folds developed during the middle Pleistocene mountain building, and therefore is younger than they are; it also fractures erosional and deformational features formed after the main deformation. Nearly everywhere along the San Andreas rift, evidence of recent



FIG. 115. A series of stepped dislocations caused by earthquake of 1906, as seen in road crossing deep alluvial fill near Salinas, Monterey County. *Photo from J. C. Branner collection, courtesy Stanford University.*

movement such as sag ponds (small depressions of limited area), small elevated blocks or buttes, offset ridges and drainage lines may be seen, while there is no similar evidence along the mid-Pleistocene faults. At the time of the 1906 earthquake, open rifts showed in the ground along 270 miles of the fault north and south of San Francisco.

Some geologists believe that great horizontal dislocation has taken place along the San Andreas rift, most of the movement having taken place in that direction, and that the offset is measurable in miles or scores of miles. Although the exact amount of dislocation is difficult to determine, it appears to be less than a mile. The maximum offset of drainage lines caused by the repeated breaks along the fault is about 3,000 feet. Thus, in spite of the 600-mile or more length of the rift,



FIG. 116. Gigantic earthflow south of Gilroy. Slides of masses of rock mantle and poorly consolidated rock are common in the Coast Ranges Province when the ground is waterlogged and slippage easy. *Photo by Clyde Sunderland, Oakland, California.*



FIG. 117. Lower end of earthflow jumble near Gilroy, showing characteristic irregularly fractured surface. *Photo by Clyde Sunderland, Oakland, California.*

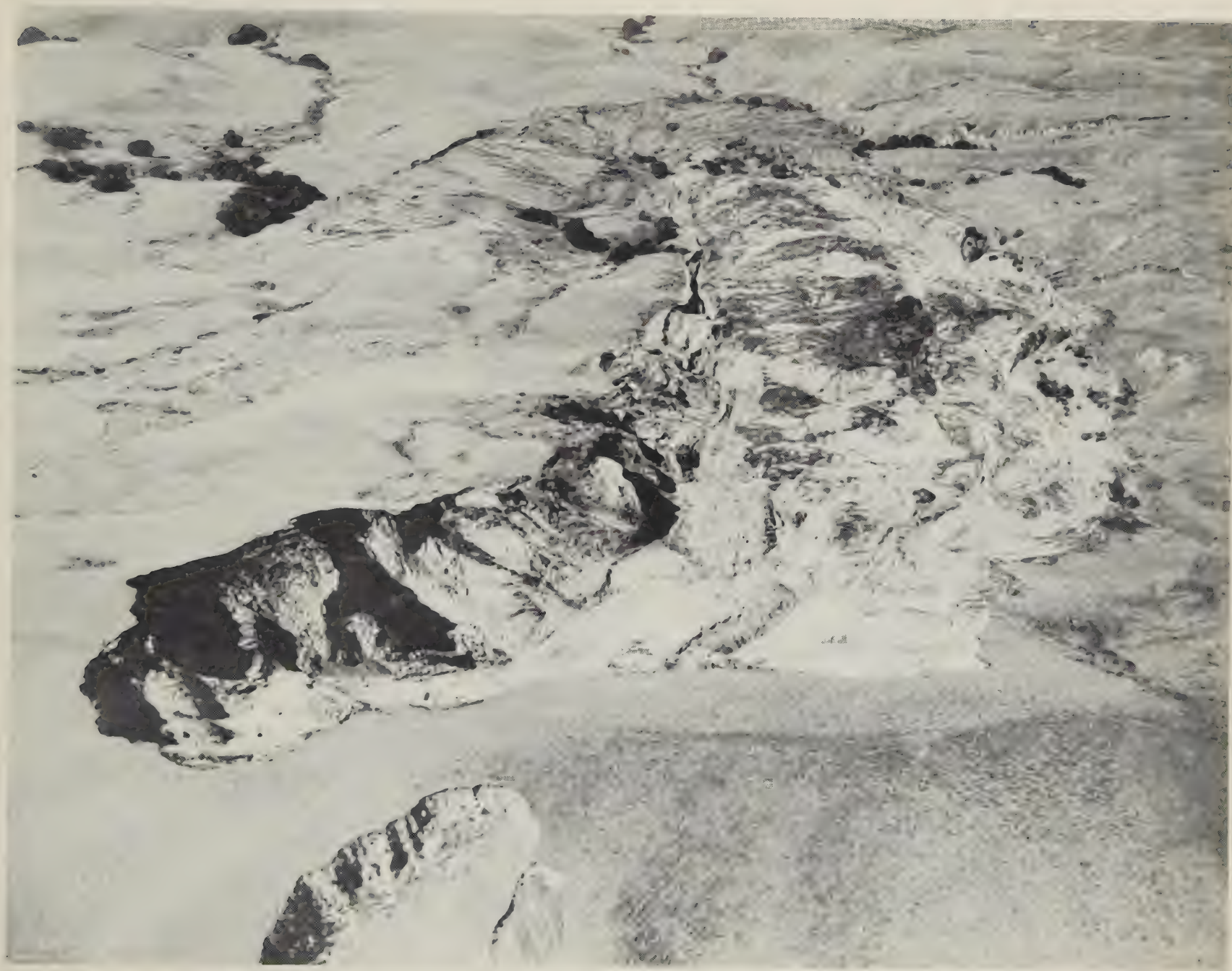


FIG. 118. Closer view of scar and earthflow jumble near Gilroy. Photo by Clyde Sunderland, Oakland, California.

it has had little influence on structure or topography developed by the intense mid-Pleistocene fold-faulting, at least in the central part of the Coast Ranges.

Valleys eroded in the crushed rock along the San Andreas rift are among the youngest land forms in the province.

San Francisco Bay Region

The hills and mountains lying west of San Francisco Bay are divided into a northern and a southern section by the Golden Gate: to the south is San Francisco peninsula; to the north is Marin peninsula with its crowning point, Mount Tamalpais, whose two summits West Peak (2,604 feet) and East Peak (2,586 feet) may be seen for a long distance.

North of the Golden Gate and the bay, the Coast Ranges consist of various ridges oriented somewhat west of north. There is little agreement on the names of most of these ranges or the area to which the better recognized names apply. Between lie Petaluma or Sonoma, Napa, Clear Lake, and Berryessa valleys, named from west to east; each is a major structural depression sharply contrasted with the lesser canyons and valleys carved into the ranges by streams. About 50 miles north of the bay, all but the Sonoma Range merge into a much dissected upland called the Mendocino Plateau which has an average elevation of 1,600 feet on the western side and 2,100 feet on the eastern where higher residual peaks of the Mendocino Range are seen. The upland without question is a subdued erosion surface developed at lower elevation in past time, later raised, and now in process of destruction. Of the major structural depressions, only the Petaluma and its extension along the Russian River project as far north as the Mendocino Plateau.

South of San Francisco Bay, the Santa Clara Valley, which is much larger than any on the northern side, separates the Coast Ranges into an eastern division often called collectively the Diablo Range and a western termed the Santa Cruz Mountains. The Santa Clara Valley is the largest structural depression of the central section of the Coast Ranges, having a length of about 100 miles and a width of 15 miles where it is flooded by the southern part of San Francisco Bay. The lower 75 miles of this valley are drained by Coyote Creek into the bay; whereas the upper 25 miles, isolated from the rest by a large alluvial fan, sends its waters first into Llago Creek and thence into the Pajaro River which empties into Monterey Bay.

The Diablo Range, the mountainous belt east of San Francisco Bay and south of the Sacramento River, is divided into several smaller northwest-trending ridges separated by valleys largely controlled by prominent faults. The highest peak in the northern part is the prominent Mount Diablo, east of Walnut Creek, which rises 3,849 feet above sea level. South of the Livermore Valley, the Diablo Range, locally known as the Mount Hamilton Range, has a width of more than 30

miles and some peaks exceeding 4,000 feet high. The Berkeley Hills, immediately east of San Francisco Bay, considered by some as a unit distinct from the Diablo Range, form a moderately rugged belt about 15 miles long and 10 miles wide with a prominent western-facing scarp. Between the main portion of the Berkeley Hills and the main portion of the Diablo Range lies San Ramon Valley, a structural depression.

West of San Francisco Bay, the Santa Cruz Mountains extend for nearly 85 miles southward from the Golden Gate to the Pajaro River. This section of the Coast Ranges is narrowest and lowest in the San Francisco Peninsula, widens and grows higher beyond, but again narrows notably at its southern extremity. The highest peaks stand about 3,700 feet above sea level. Northwest-trending structural valleys are present in the Santa Cruz Mountains but are less conspicuous than in the Diablo Range.

The crests of many of the Coast Ranges both north and south of San Francisco Bay are broad, rolling uplands. Peaks and ridges rise above the upland both in the south and the north. In the Santa Cruz Mountains two erosion surfaces are present, one at 600 feet and the other between 1,100 and 1,200 feet, but it is uncertain whether they are two distinct erosion levels or parts of one separated by faults. Elsewhere there is a single well advanced landscape now being deeply trenched by young canyons cut because of the elevation of the ranges.

The Santa Clara Mountains are separated into two parts by Merced Valley which runs westward from the bay to the ocean. On each side is a much eroded tilted fault block having a west-facing scarp and a gentle back slope. The high point of the northern block is San Bruno Mountain (1,315 feet), while that of the southern block is Montara Mountain (1,952 feet). Separating the two blocks is the San Bruno fault lying at the base of the steep southwestern front of San Bruno Mountain.

The northern block is irregularly hilly, and except in San Bruno Mountain, there is little parallelism between hills and valleys and the trend of the block. The topography is generally subdued though certain rugged areas of resistant chert stand out. Chert is a rock composed of almost pure silica. On the other hand, in the southern Montara section, crests and valleys run parallel to the long axis of the block and the topography is much more vigorous than in the San Bruno Hills. The most notable feature of the Montara block is the valley containing San Andreas and Crystal Springs lakes and through which runs a portion of the great San Andreas rift. This valley has been partly formed by earth movements along the fault but more important has been the easy erosion of badly crushed rock in the fracture zone. Northeast of this valley lies Buriburi Ridge which slopes to Merced Valley and San Francisco Bay. San Mateo Creek cuts transversely across this ridge draining the San Andreas rift valley and flowing through a narrow gorge to the Bay.



FIG. 113. Sand dunes in a cove at Pismo Beach along the Coast Ranges shore. The asymmetrical form of the dunes is clearly shown; the gentle slope is in the direction of the prevailing wind. Photo courtesy Spence Air Photos.

SPENCE
Air Photos



FIG. 120. Mt. Diablo, a fault block of complex structure in the Coast Ranges. Photo by Davies. Norman E. A. Hinds, *GEOMORPHOLOGY* (copyright 1943 by Prentice-Hall, Inc., New York). Reproduced by permission of the publisher.

The slope of the Montara block southwest of the rift valley is broken by a series of narrow canyons and ridges which are in large part remnants of the original erosion surface tilted upward as the block rose. Along the southwest base of Montara Mountain but separated from it by an alluviated valley is a low ridge known as Miramontes which terminates oceanward in Pillar Point.

The shorelines of the two sides of San Francisco Peninsula are markedly different. On the Pacific side vigorous wave attack against the mountains has developed long stretches of sea cliffs with sandy or pebbly beaches at their base; coves between headlands are well filled with sediments brought in by rivers, waves, and currents. There are only a few prominently projecting points like San Pedro. Off the headlands stand rocky islands, like the Seal Rocks on the south side of the Golden Gate, which have been isolated by the wave attack and are gradually being destroyed. In contrast the bay-side shoreline is highly irregular with tidal marshes and other evidences of deposition in numerous bays between conspicuous promontories. Cliff erosion is feeble and there are no clean sandy or pebbly beaches. The shore features on the bay side especially indicate rather recent submergence of a considerably eroded land mass. Similar submergence also is indicated along the oceanic side of San Francisco Peninsula, as for example at Lake Merced, which before it was modified for use as a reservoir, was a drowned valley cut off from the ocean by a bar of drifting sand. The Golden Gate is another illustration: there the ocean has invaded a young canyon which the Sacramento River had cut across the mountainous barrier.

Sand dunes are abundant along the Pacific side of the Peninsula. The sand is brought to the ocean by streams or is prepared by the attack of waves on rocks along the shore line. Prevailing winds drift this debris for a considerable distance inland, forming dunes or scatterings and irregular piles of sand called drifts. This encroachment has been largely checked in certain places by building of city improvements or planting vegetation. This was one of the prime purposes of the establishment of Golden Gate Park.

Marin Peninsula, north of the Golden Gate, is a continuation of the mountainous section to the south and is separated from it by the narrow channel through which the ocean has spread to form San Francisco Bay. The mouths of stream valleys descending to the ocean from the highlands have been embayed indicating either that the Peninsula has sunk or that the ocean, rising as the ice of the fourth glacial stage melted, has invaded the lowest parts. From the highest point, Mount Tamalpais, a ridge extends west and northwest for a considerable distance. The slopes from the peaks and from the ridge are steep in all directions and are broken by deep gorges between which lie narrow ridges. However, where these canyons approach the shoreline, they widen and their floors are flat, mostly salty marshes, a product of sedimentation in the embayments. This is notably true on the bay side of the peninsula, where Tiburon Peninsula and San Quentin Point separate three main bays reaching far inland to the base of the mountains. Each of these indentations has a wide sedimentary fill, the delta plain of the stream which carved the valley. On the western side of Mount Tamalpais, ridges and valleys either descend to the sea or to a long valley separating the peak from the Point Reyes Peninsula.

Besides the Golden Gate, Elk Valley crosses Marin Peninsula from the head of Richardson Bay to the head of Tennessee Cove. This valley, while possessed of rather low bottom slope, has steep walls and lies almost at right angles to the trend of the Marin block. Its origin is not yet fully understood. The bottom is alluviated to some extent by wash from the walls.

Point Reyes Peninsula is geographically distinct from the main part of Marin Peninsula to the east and is separated from it by a long narrow valley through which passes a section of the San Andreas rift. The north end of this valley has been submerged by the ocean forming Tomales Bay, while the south end terminates in Bolinas Lagoon which is separated from the sea by a wave-built sand spit. The formation of the valley, like a similar one previously described in the Montara fault block south of the Golden Gate, has been partly the result of earth movements along the great fault but more important has been the easy erosion of crushed rock along this fracture zone. The quite straight eastern margin of the Point Reyes Peninsula parallels and lies close to this rift valley; from the ridge along this eastern bound-



FIG. 121. Coast south of San Francisco. The relatively straight shore line, prominent cliffs, few projecting headlands, and clean, sandy beaches are characteristic. Highland in the foreground is the Monterey block. To the north are Merced Valley and the San Bruno block. In the background is Mt. Tamalpais, high point on the ridge extending north of the Golden Gate. *Photo by Fairchild Aerial Surveys.*



FIG. 122. Golden Gate, San Francisco. The deepest water in Golden Gate strait measures 381 feet. Golden Gate Bridge connects the San Francisco and Marin County sides of the strait. The hills in the background culminate in Mt. Tamalpais, highest point in Marin County. *Photo by Spence Air Photos.*



FIG. 123. Landslide of December 9, 1950, on Tunnel Road (State Highway 24) between Oakland and Orinda. Trees brought down in the slide and the earth moving equipment in the right foreground indicate the size *Photo by Bill Young, courtesy San Francisco Chronicle.*

ary, the general slope is toward the ocean. Streams have channeled the surface and their lower ends have been drowned by invading sea water.

At the south end of Point Reyes Peninsula is one of the finest wave-cut terraces along the California coast. The surface is quite even but does slope gently upward from its outer margin to much eroded sea-cliffs whose base stands about 250 feet above the sea. The terrace is being dissected by small streams flowing to the ocean from the higher land along the eastern side. Along the western side of the main part of Point Reyes Peninsula there is no comparable terrace, a fact for which we have no explanation.

As with most of the Coast Ranges province, landscape evolution in the San Francisco Bay area has been complicated and is far from being perfectly understood today. None the less many pertinent facts are known which give at least some understanding of the history of this magnificent harbor which is matched in few places round about the world. The bay occupies part of a long valley lying between and almost completely enclosed by prominent hills, a setting which contributes to its beauty. Along the western shore, headlands and peninsulas project into the water and are separated by canyons extending far into the hills. In contrast about 40 miles of the eastern side is bordered by a low plain which slopes gently to the base of the Berkeley Hills; above the surface of this plain project a number of low hills and ridges. Islands like Angel, Yerba Buena, Alcatraz, and Red Rock rise boldly above the bay surface. Treasure Island which extends northward from Yerba Buena is an artificial construction used as the site of the Golden Gate International Exposition of 1939 and now of a great naval establishment. There also has been considerable addition to the land along both eastern and western shores of the bay by man-made fills.

Most of San Francisco Bay is shallow, being less than 18 feet deep with 85 per cent less than 30 feet. There are, however, deep channels, courses of the principal streams flowing through the valley before it was submerged; tidal flow has developed in these channels, a sort of submarine stream system which keeps them swept relatively free from sediment. The greatest depth of water (381 feet) is in the main trunk channel through the Golden Gate, while in the main branch to the north, Racoon Strait, the maximum depth is 185 feet.

During the middle Pleistocene mountain building large scale block faulting and other deformation occurred in the San Francisco Bay region roughly outlining the area later to be partly submerged by the ocean. It is possible that the later and relatively mild deformation which produced the San Andreas rift and certain other features may have caused sufficient subsidence to allow the sea to enter the Golden Gate and spread farther inland. The submergence was greater along

the western than along the eastern side of the lowland, as the major flooding occurred there. The submergence was local; the valleys of the Russian River 50 miles north of the bay and the Pajaro River 50 miles south were not drowned. Bolinas and Tomales bays were established along the San Andreas rift valley in Marin County, while Drakes Bay near Point Reyes seems to have been formed by the entrance of ocean water into the head of a valley system which drained southward toward the Golden Gate. Subsidence may have continued to the present, for a large shell mound on the east side of San Francisco Bay near Emeryville stands more than 2 feet below sea level and similar situations exist elsewhere. However, another explanation of the bay's origin must be considered.

It is not definitely known when the drainage from the Great Valley began to reach the sea in the vicinity of San Francisco, but certainly there is no evidence of such a system prior to the late Pliocene deformation. Some have thought that the Sacramento River did not flow to the Pacific Ocean through the Golden Gate but rather was directed southward through Santa Clara Valley to Monterey Bay. The preponderance of evidence now at hand opposes the latter concept.

The depression partly occupied by the bay has long been regarded as being primarily the product of deformation though it is also well known that its contour has been modified by erosion and deposition before the bay appeared. Early explanations called for the tilting of fault blocks along fracture zones, the eastern edge of the San Francisco-Marine block lying against the base of the Berkeley Hills. But the Hayward fault, the great structural boundary at the western base of the Berkeley Hills, is not located where such a margin should be under the terms of the foregoing explanation. The boundary of the southern part of the bay had been thought to be the Montara block which was tilted up to the west along the San Bruno fault. However, it is difficult to fit the distribution of land masses and topography into any definite adjustment of major fault blocks. The bay valley crosses supposed boundary faults on both sides and transgresses adjoining blocks. The valley passes at various angles over all medium to large faults in its vicinity and cuts across other structures both young and old. Only for limited distances does it follow one or the other. Therefore the most reasonable origin of the depressed area seems to be downwarping with some slopes formed by normal open folds while others are the product of faulting distributed along zones of various widths.

The elevation of the Berkeley Hills seems to have been a prime event in the evolution of the bay district and the first rise of this block at the time of the late Pliocene deformation may have coincided with the initiation of the depression now partially flooded by ocean water. During the middle Pleistocene mountain building, the re-elevation of the Berkeley Hills was slow enough so that the Sacramento River



FIG. 124. Yerba Buena Island (foreground), an erosion residual in San Francisco Bay; tip of San Francisco Peninsula to left, in background, Marin hills to right. Extending from the north of Yerba Buena is Treasure Island, an artificial construction now a naval base. Photo by Spence Air Photos.

maintained its course across them, eroding Carquinez Canyon, now Carquinez Strait, to a depth of 800 or 900 feet. Possibly simultaneous elevation occurred on the west side of the bay and at slow enough rate so that the river kept its channel and cut Golden Gate Canyon, now Golden Gate Strait, to a depth of more than 700 feet. The lower course of the Russian River north of the bay and of Alameda Creek on the south side also seem to coincide with their position before the elevation of the ranges. On the other hand, most drainage was obstructed by the rise of ridges athwart their paths and the former stream courses are now represented by abandoned channels called wind gaps of which Racoon Pass, Liberty Gap, and Elk Valley are examples.

A number of streams tributary to the Sacramento River before advent of the bay entered the main valley through open, V-shaped valleys whose bottoms are now 150 to 200 feet below sea level. Borings have shown that these streams were flowing on bedrock and therefore were downcutting instead of wandering over broad alluvial fills as they do today on their way to the bay.

Most of the bay valley had considerably more diverse topography than the part immediately along the main river, being traversed by hills trending in directions somewhat diagonal to the main axis of the valley. Examples of these are the Potrero San Pablo west of Richmond, Coyote Hills west of Newark, San Mateo Point, and El Cerrito Hill. Other pronounced eminences are the various islands, while lower hills and ridges now submerged by ocean water have been revealed by borings.

Very late in earth history came the flooding of the canyons and associated lower parts of the valley region, developing the first stages of the drowned valley which was to expand into the present large-sized bay. Such embayments in many cases are the product of deformation, yet evidence has been obtained in the San Francisco Bay region showing that for some time prior to the invasion by the ocean, the rivers were actually eroding rising ground. This is particularly true north of the bay and along Carquinez Strait.

We are now aware that many bays have been evolved by the rise as the great ice sheets and other glaciers of the last glacial stage melted or receded. However, in most cases it is not possible to tell whether all of the submergence resulted from increase in the volume of the ocean or whether deformation also played a part. Evolution of San Francisco Bay by rise of sea level is consonant with much evidence which has been accumulated regarding the recency of its appearance, for the flood spread not only over the depressed area but also over some that was rising.

The ocean first entered the mouth of Golden Gate Canyon which was being eroded in bedrock. Sea level has probably risen about 350 feet since the beginning of the submergence. Most of the ice appears

to have melted during the last 25,000 years of earth history, hence the main development of present-day San Francisco Bay must have occurred during that interval.

The growth of the bay of course was slow. At first the streams retained their way to the ocean by way of the trunk channel through the Golden Gate, though tidal marshes gradually developed along their margins. As the ocean continued to rise, it drove the mouth of the Sacramento River back, progressively isolating tributary streams. Some hold that 10,000 or 15,000 years probably elapsed before Carquinez Canyon was invaded and the ocean rolled into the lowlands of the Great Valley forming Suisun Bay. In fact the growth of the bay may have come very much closer to our time than the date just indicated.

From recent studies of sea level changes during the last glacial stage, some authorities believe that the lowering of ocean level did not amount to more than 250 feet. If this is correct, the picture just drawn must be modified somewhat. The bay may have existed on sunken land prior to the beginning of the last glacial stage, then grew very much smaller as sea level fell, and finally assumed its existing dimensions as the ocean rose in exceedingly late geological time.

With increase in the depths of the bay, it became a basin in which settled great volumes of sediment transported by the Sacramento River and its former tributaries. Advent of man to the region contributing sediment has greatly accelerated the rate of deposition, mostly from hydraulic mining, but also the result of ever increasing farming, overgrazing, improper lumbering, forest fires of human setting, and other activities. The great bulk of sedimentation is at the north end of the bay, but the southern end also gets a considerable volume. Deltas have been constructed at many of the stream mouths and their inner parts have grown above sea level as delta plains like those of Napa and Petaluma Creeks. Sedimentation is sufficiently rapid so that the bay will be filled in a relatively short geological interval unless deformation intervenes to deepen it.

Beyond the Golden Gate and extending past the Farallon Islands lies the continental shelf which is wider in this section than along most of the California coast. The shelf probably represents in part the delta of the Sacramento River when it flowed into the Pacific Ocean through the narrow gorge of the Golden Gate, but it has been added to by sediment carried from the bay during the flood season and dropped beyond this strait.

Rising above the low plain bordering the west side of San Francisco Bay or from the bay itself is the rather rugged, low, hilly block known as the Berkeley Hills. Some hold that this unit is part of the Diablo Range while others consider it a separate mass. The principal ridges in the Berkeley Hills are directed southeastward and the valleys between them have been etched by streams either into weak layers



FIG. 125. Low plain at base of Berkeley Hills. At the western base of the hills is the Hayward fault. *Photo by Spence Air Photos.*



FIG. 126. University of California, in the Berkeley Hills. The Hayward fault system lies at base of the hills passing under stadium. *Photo courtesy U. S. Army Air Corps.*



FIG. 127. Mount St. Helena at the corner of Napa, Sonoma, and Lake Counties, is composed of fragmental volcanic rock. Photo by Clyde Sunderland, Oakland, California.

between those more resistant or into crushed rock along faults. The high points on the main ridges are Bald Peak (1,930 feet), Grizzly Peak (1,769 feet), Round Top (1,750 feet) and Redwood Peak (1,608 feet).

The Berkeley Hills block is bounded on the southwest by a zone of intense deformation in which the principal feature is the active Hayward fault. It is quite certain that the zone of weakness considerably antedates in origin the fault just referred to, a situation comparable to that found along part of the San Andreas rift. It is possible that the Hayward and San Andreas systems join southward near Hollister, though this has not been positively demonstrated.

Along the Hayward fault there are basins and buttes similar to those along the San Andreas rift. One particularly well developed basin contains the southernmost green of the Berkeley Country Club; this may be seen just east of Ardmore Road which leads from Berkeley to Richmond. Perhaps the most striking feature along the rift is a long, narrow, interrupted valley between Claremont Creek and the vicinity of Hayward. As the western scarp of the Berkeley Hills grew in height, consequent streams began to flow down it and carve young canyons; this drainage is directed southwestward. Thus the valley following the Hayward rift and paralleling the trend of the Berkeley Hills is out of accord with the normal trend of valley development. In this section between Claremont Creek and Hayward, most of the drainage has been diverted for short distances along the rift valley before it returns to a normal southwesterly direction through breaches in the rift valley walls. The western slope drainage of the Berkeley Hills therefore appears to be older than the rift valley, where erosion has been made easy by the abundance of crushed rock developed as adjacent blocks have moved along the fault. Thus it appears that the Hayward fault is younger than the main fracture zone separating the Berkeley Hills and the San Francisco-Marin blocks, just as the San Andreas fault is younger than that along which the San Francisco and Marin County and the Marin blocks are displaced.

In addition to the Sacramento which held its course across the rising Berkeley Hills, another notable drainage feature was the deflection into Alameda Creek of water which formerly flowed through Livermore, San Ramon and Ygnacio Valleys into Suisun Bay. This drainage alteration, an example of stream capture, explains the contrast between the large San Ramon Valley and the small creek flowing through it. Alameda Creek flows through a deep, narrow canyon in the Berkeley Hills after receiving drainage from Mount Diablo and the Mount Hamilton range and flowing through broad valleys east of the Berkeley Hills. Its course between Sunol and Niles evidently was established before the elevation of the hills, whose rate of uplift was such that the stream was able to match it, eroding the canyon which it now occupies. Such streams, of which the lower courses



FIG. 128. Trench being dug along dike wall composed of firmly compacted gouge or fine rock fragments. As dike is relatively impermeable, the water level on the east (left) side stands several feet higher than on the west (right) side. Photo by Alameda County Water District.

of the Sacramento and the Russian River are examples, exist before the appearance of a mountain range, continue to flow across it through deep canyons, and thus are said to be *antedecedent* to the uplift.

In excavations along the Hayward rift fragmented rock of the crushed zone has been exposed. Well illustrated at many places are the polished, scratched, and grooved surfaces produced by the grinding of rock masses against each other.

This zone of deformation also is marked by a series of step-faults which produce a terraced front in the hills like that particularly well shown between Strawberry and Cordonices Creeks. North of Cordonices Creek such faults, although present, have had little effect on the topography.

Many other faults are present in the Berkeley Hills but topographic features like those described along the Hayward rift do not show along most of them, indicating that they are of greater age.

The structurally controlled ridges in the block have been abundantly sculptured by streams so that there is a myriad of deep, young gorges trending roughly at right angles to the courses of the principal ridges. The spasmodic nature of the elevation of the block is illustrated by a succession of river cut terraces in many of the canyons.

Clear Lake in Lake County is the largest landslide lake in the state. The basin is a former plain 25 miles by 15 miles in size, which was drained by two outflowing streams. One of the streams, Cold Creek, had cut a deep gorge westward to the Russian River; the other stream, Cache Creek, eroded a still deeper canyon through the range on the eastern side of the basin and eventually joined the Sacramento River. The eastern stream was later broken or had its course displaced near the entrance to its gorge by a small lava flow and the water was diverted into Cold Creek.

Only a few centuries ago a large landslide, breaking loose from the middle part of the southern side of the western gorge, filled it up for a mile or more to a higher level than that of the surface of the lava flow on the other side of the basin. This dam backed up waters from the streams flowing into the Clear Lake basin until they finally overflowed to the east through a sag in the lava flow at the mouth of Cache Creek canyon. The overflow cut Red Bank Gorge across the flow, re-established the drainage into Cache Creek canyon, and reduced the lake level about 60 feet. If this eastern outlet had not developed, the lake level would have risen until it overtopped the landslide barrier, which would probably have been eroded so that most or even all of the basin would have been drained. But because of the eastern outlet, surface rills and leakage through the slide can do it little damage on account of its great size.

Since the early days of the lake, the narrow embayment that occupied the western gorge back of the landslide dam has been isolated from the main part by the broad delta of Middle Creek coming in from the north and has been further shortened by another delta, that of Scott Creek entering from the south. The remainder is divided into the two little Blue Lakes by combined delta plains of two wet-weather streams.

Clear Lake was artificially modified more than 30 years ago by construction of a 30-foot dam at the entrance to the eastern gorge and by blasting a rocky barrier to a slightly greater depth near the entrance of the eastern outlet stream through the lava barrier. This made possible the storing of a greater volume of water from the winter rains and of withdrawing it to lower than normal lake level for irrigation of rice fields in the Yolo Basin of the Sacramento River during the summer time. As a result the lake level now usually stands a few feet above shore beaches formed before these alterations were made. However, the 25 to 30 inches of annual rainfall over the Clear Lake basin does not supply the inflowing streams with much more water than is lost by evaporation from the lake, hence the amount available for irrigation is small.

Recent field work may alter to some extent ideas concerning the parts played by the landslide and lava flow in the development of the lake. The study indicates that the deformation basin probably was

of sufficient depth to have held a lake of some size had neither of the barriers been present and that it had been an area of sedimentary deposition for a long time, the debris being accumulated partly by rivers and partly in lakes.

Volcanic Activity

Pleistocene lava flows and volcanic cones are present around the southern margin of Clear Lake, largest natural body of water in the California Coast Ranges. Of the volcanic features Mount Konocti, rising 2,800 feet above the lake, is most conspicuous.

Mount Konocti is an eroded multiple volcano, the highest part being south of the center of the mountain and including three prominent peaks, one of which apparently is the remnant of a secondary cone. About a mile north of this group Mount Buckingham, part of the volcano, stands at somewhat lower elevation and there are other small secondary peaks.

In the visible part of the volcano, lava flows are most common, though fragmental deposits show on the lower western flanks and at other scattered areas. Konocti therefore is a composite cone.

There are remnants of several craters, the best example being Southern Peak, which has a shallow summit depression; another, apparently larger example lies farther north and includes Howard Peak, highest point on the volcano. Small cinder cones dot the flanks as is so common in composite and shield volcanoes.

The amount of erosion indicates considerable antiquity, the main activity having ended in middle or rather well back in late Pleistocene time. At the summit of Buckingham Peak, there is newer looking fragmental material indicating possibly more recent eruptions from this northern summit.

Southeast of Kelseyville on the western side of Clear Lake are several square miles of pumice-tuff and breccia which appear to be the oldest volcanics of Mount Konocti. Most of the mountain, however, has been constructed from flows 50 to 60 feet thick; some tuffs and breccias are found between the lava flows.

Lavas south and east of Mount Konocti are similar to those composing the mountain and might appear to have come from it, but field evidence suggests that they actually were viscous flows erupted from a number of local vents. This is illustrated by Thurston Lake basin which is surrounded on all sides by steep lava walls that are the fronts of lava flows, the basin being formed because the flows coming from the various sides did not coalesce. Several small meadows in the same area probably are filled lake basins formed in similar fashion. The elevation of Thurston Lake is about that of Clear Lake, but its level fluctuates considerably. The water is fresh in spite of lack of outlet apparently because of sufficient seepage through the lavas to prevent concentration of salts. It has been suggested that Thurston Lake may have been isolated from a larger Clear Lake by eruption of the flows.



FIG. 129. Mt. Konocti, a composite volcano near the southern end of Clear Lake in Lake County. Mt. Konocti became extinct relatively late in geologic time. Clear Lake, in foreground, occupies part of a structural depression in the northern Coast Ranges. *Photo by C. W. Chesterman.*



FIG. 130. Sketch from aerial photograph across Clear Lake toward the northwest. 1, Thurston Lake basin; 2, lava field of Mt. Konocti; 3, Buckingham Peak, a portion of Mt. Konocti; 4, Little Borax Lake; 5, Buckingham Peninsula; 6, High Valley; 7, Borax Lake. Sketch by C. A. Anderson from photograph by Erickson.

Beyond the area just described there are older flows of obsidian and other lavas covering an area of about 12 square miles. Most of the flows are deeply weathered and the area is covered by dense chaparral so that it is difficult to explore. These lavas also were apparently highly viscous when erupted as their hummocky surface forms indicate. The centers from which the flows came are unknown.

Of much later age are lava flows and cinder cones erupted since the development of the existing major features of the landscape. The age of the eruptions cannot be accurately determined, but lack of much weathering and erosion suggest that they have occurred in the last few thousand years. Precipitation in the region (about 30 inches annually) has been enough to produce soil which supports a covering of chaparral and conifers.

The best known of the recent volcanic areas is *Sulphur Bank* where solfataric (hot gas) activity still goes on and has decomposed a recently erupted flow in part to white opal. Sulphur has been deposited at the same time, from oxidation of hydrogen sulphide gas as it escapes into the air. Mining of sulphur started about 1865, and at shallow depths, the mercuric sulphide, cinnabar, was later found; from 1873 to 1945 the area was intermittently mined for cinnabar, but hot water and gases interfered with underground operations.

The lava at Sulphur Bank appears to have come from a vent underlying the flow, which occupies an area of less than one square mile. The center of intense solfataric action is limited to the south-central part of the flow and may coincide with the vent from which the eruption came. Decomposition of the rock has been accomplished by sulphuric acid, formed by surface oxidation of hydrogen sulphide given off from the solfataras and hot springs. The decomposition has proceeded spheroidally, masses of fresh lava being surrounded by shells of opalized rock. Sulphur and more rarely cinnabar have been deposited in these shells.

A mile or two northeast of Sulphur Bank, two cinder cones rise from an alluviated stream valley; both have been breached on their western sides probably by explosion, for the cones have not been much eroded. The base of each volcano is about a mile in diameter and the elevation close to 400 feet. Between the cones is a low ridge composed of lava fragments capped by a thin flow of basalt which apparently came from an opening between the cones. The fragments composing the little volcanoes have been more or less reddened by oxidation.

High Valley is an east-west depression several miles northwest of Sulphur Bank which has a length of about 3 miles and width of about a mile; probably it is a small fault basin or graben which at one time may have been occupied by a lake, later drained by headward erosion of a tributary to Clear Lake.

The eastern part of High Valley contains a recent flow of blocky lava. A mile and a half east of this flow, a quite symmetrical cinder cone rises 400 feet above the lava field. In the top is a well preserved shallow crater about 300 feet across and 40 feet deep. The cone is old enough so that soil has developed in which some chaparral has taken root, but the slopes are almost undamaged by erosion. At the west base of the cone are two flows, one partly buried by fragments blasted from the volcano and the other later and not so covered. This lava field extends eastward as far as the North Fork of Cache Creek.

There is evidence of recent volcanic action south of Borax Lake where an older flow is buried by a later outpouring which solidified as obsidian. The older body is rather thin with a front 15 to 25 feet high and is mostly made of blocky lava, though on the western edge the top is red and scoriaeous. The black obsidian above has a steep front 40 to 50 feet high; its top has broken up considerably so that fragments of the rock are interbedded in soil. It is possible that the opening from which the flow came lies in the northern part of the field, where there is a hill of pumiceous lava rising 30 to 40 feet above the obsidian surface suggesting that the last of the lava erupted was so viscous that it was elevated as a dome.

Borax Lake occupies a shallow depression northwest of the obsidian flow. Occasionally it dries up. The source of the borax appears to be the northeast end of the obsidian flow where some solfataric action has recently occurred. Some sulphur is present but the obsidian is not badly decomposed. The solfataric action is now weak, though the ground is moist and warm and a faint odor of hydrogen sulphide pervades.

The most southerly of the recent cinder cones surmounts recent flows less than a mile southeast of Thurston Lake. Like the Sulphur Bank cones it is breached, opening to the northeast. A flow of basalt extends to the east of the cone and probably is of later date.

Chalk Mountain, east of the North Fork of Cache Creek, is a small conical hill about 400 feet high. The lava has been altered giving a brilliant white color which makes the hill a prominent landmark easily visible from the Williams-Clear Lake highway (No. 20), which runs 4 miles to the south. Chalk Mountain apparently is a plug dome, extensively bleached and decomposed by later solfataric action. There is some discharge of cold water containing hydrogen sulphide on the western side of the dome, and the same gas can be detected at the top. Otherwise the vents are inactive. Stream terraces at the western base have been coated with white spring deposits testifying to the recency of the gas action. It is thought that the Chalk Mountain dome was elevated within the last few thousand years.

Little Borax Lake occupies a shallow crater at the base of steep slopes descending from Buckingham Peak. This crater apparently was produced by a gaseous eruption without ejection of fresh lava for none of the fragments appears to have been liquid when blasted out.

The water of the lake is saline and is said to deposit borate and carbonate minerals. Some lime deposits are above water level along the south side, but there is no hot spring action now.

South of Mount Konocti are several isolated patches of basalt which have been partly eroded. They evidently were erupted after the development of the major landscape features in this section, but probably are older than the other volcanic rocks belonging to the last cycle.

Pinnacles National Monument

Pinnacles National Monument is between Salinas and San Benito valleys in the Gabilan Mountains, a division of the California Coast Ranges. It is 35 miles south of Hollister and about an equal distance north of King City. The area, because of its remarkable topography, was set apart as a National Monument by President Theodore Roosevelt in 1908 and has been considerably added to since that time. The monument is most accessible from the eastern side by a branch of a road leading south from Hollister. Good trails have been constructed so that the principal scenic features are within reach of hikers.

As the name suggests, the monument is an astonishing galaxy of rocky crags, spires, and pinnacles which make a most bizarre landscape.

The area is not particularly high. Chalone Valley has an elevation of about 1,000 feet, while nearby North Chalone Peak, highest point in the monument, stands 3,297 feet above sea level. Hawkins Peak, a spectacular assemblage of pinnacles, is more than 2,600 feet high.

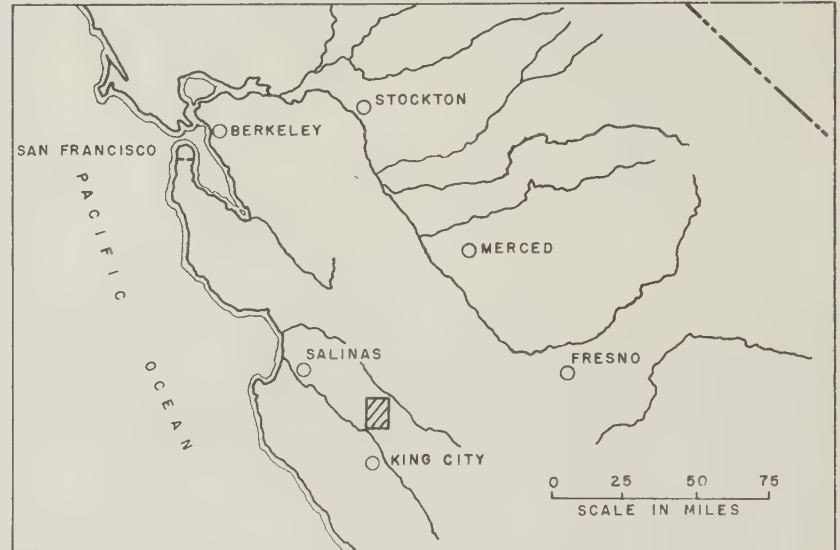


FIG. 131. Map showing location of Pinnacles National Monument.
After Phillip Andrews.

Millions of years ago, this section of California was a vigorous volcanic field. Many lava flows were erupted and still greater thicknesses of exploded products which were cemented together into volcanic breccias. In the breccias the principal erosional features were sculptured after the rock had been broken by great numbers of prominent joints. Weathering along these fractures loosened fragments which have been removed by gravity and running water, perhaps a minor number by wind, thus enlarging the joints and evolving a weird complex of land forms. Deposition of silica from water migrating through the breccias has greatly hardened certain parts, allowing them to stand out from adjacent more easily erodable material. The lava flows also have been abundantly jointed in places so that they have behaved much like the fragmental deposits in the formation of pinnacles.

Natural caves of rather large size are present along both branches of Chalone Creek, principal stream of the monument, which has undercut beds of massive breccia. In scouring out less resistant material, the

excavation has been so extensive in places that large, unsupported masses have slumped down. A short distance from the Pinnacles Ranger Station, a subterranean chamber nearly 100 feet across and in total darkness except when artificially illuminated, has been formed by a single block of massive breccia supported around the edges by smaller blocks. Large joint blocks also have rolled down the steep canyon slopes aiding the formation of the caverns.

Except for Chalone Creek, streams flow through the monument only during and after heavy rains. The distinctly arid climate helps to preserve the angular outlines of the landscape and prevents the formation of a heavy soil cover.

Prior to the beginning of the volcanic episode, long erosion had reduced this section of California to a lowland of very subdued relief etched in various kinds of rocks with granite being the chief type in the monument. The resistant granite basement was broken by numerous fractures probably during a later deformation and along these rose masses of rhyolitic magma which solidified as sills and dikes, some of which were undoubtedly feeders for the flows poured out on the surface. The earliest surface eruptions were rhyolite flows which piled one upon another in considerable thickness, though somewhat later andesitic and basaltic magmas also were poured out. In the last stages of this flow episode, the lava apparently became quite viscous and a large, steep-sided mass was elevated along one of the fractures forming a volcanic dome having an elongate pattern contrasting with the more or less nearly circular examples in Lassen Volcanic National Park, Mount Shasta, and the Mono Cones on the east side of the Sierra Nevada.

Then from five nearly circular vents and possibly more, explosive eruptions blasted out great quantities of solid and liquid fragments. The largest center was that of South Chalone; the others definitely known follow a roughly north trend. The centers can be identified because explosions filled them with layered masses of rhyolitic tuff while round about is massive rhyolite. In these *vent-fillings*, as they are called, conical pinnacles have been carved by erosion.

The eruptions occurred during Miocene time, the third epoch of the Cenozoic era, consequently much evidence regarding them has been destroyed by erosion. Probably the massive breccia deposits were formed by several agencies including various types of violent volcanic explosion and the crumbling of the walls of the steep rhyolitic dome which formed a deep mantle of talus. Many flows followed

explosive eruptions, enveloping great quantities of fragments and cementing them together. Other flows broke into brecciated masses as they advanced. Avalanches and the natural angles of repose of this coarse material maintained the steep slopes of the dome ridge.

The length of the volcanic episode cannot be estimated, but it must have been long, as more than 4,500 feet of fragmental debris is left and in addition a considerable thickness of lava flows. In addition, both explosive and flow eruptions were repeated after interruptions of various lengths during which volcanic activity virtually ceased and weathering and erosion of the volcanic deposits took place.

Faulting that occurred after the close of the volcanic cycle displaced rocks along the fractures considerably. Three principal faults are present in the Pinnacles National Monument, all of them being roughly parallel to the San Andreas fault which lies a few miles to the west. Erosion has removed volcanic rock from areas elevated along the fractures so that the original extent of the deposits cannot be determined, but it certainly has been considerably reduced. In quite late time the elevation of the region has caused conspicuous erosion by invigorated drainage.

REFERENCES

- Anderson, C. A., Volcanic history of the Clear Lake area: Geol. Soc. America Bull., vol. 47, pp. 627-664, 1936.
- Andrews, Phillip, Geology of the Pinnacles National Monument: Univ. California Dept. Geol. Sci. Bull., vol. 24, pp. 1-38, 1936.
- Davis, W. M., The lakes of California: California Div. Mines Rept. 29, pp. 175-236, 1933.
- Howard, A. D., Development of the landscape of the San Francisco Bay counties: California Div. Mines Bull. 154, pp. 95-106, 1951.
- Lawson, A. C., The geology of Carmelo Bay: Univ. California Dept. Geol. Sci. Bull., vol. 1, pp. 1-59, 1893.
- Lawson, A. C., U. S. Geol. Survey Geol. Atlas, San Francisco folio (no. 193), 1914.
- Lawson, A. C., and Palache, Charles, The Berkeley Hills, a detail of Coast Range geology: Univ. California Dept. Geol. Sci. Bull., vol. 2, pp. 348-450, 1902.
- Louderback, G. D., Characteristics of active faults in the central Coast Ranges of California with application to the safety of dams: Seismol. Soc. America Bull., vol. 27, pp. 1-27, 1937.
- Louderback, G. D., Geologic history of San Francisco Bay: California Div. Mines Bull. 154, pp. 75-94, 1951.
- Taliaferro, N. L., Geologic history and structure of the central Coast Ranges of California: California Div. Mines Bull. 118, pp. 119-163, 1943.
- Weaver, C. E., Geology and mineral deposits of an area north of San Francisco Bay, California: California Div. Mines Bull. 149, 1949.

TRANSVERSE RANGES

TRANSVERSE RANGES

Within the Transverse Ranges, an east-west system in southern California, is a structural depression extending eastward from the coast and reaching south of the Mexican border. The basin is the most heavily populated section of California containing such cities as Los Angeles, Long Beach, San Diego, Pasadena, San Bernardino, Riverside, Redlands, and many others. It is a great agricultural region and is becoming increasingly industrialized. The Transverse Ranges consist of the Santa Ynez and other low mountain groups and intervening valleys such as the Ojai and that of the Ventura River and the Santa Monica Mountains farther south which extend from Los Angeles to the coast. Separated structurally but a part of the transverse system and undoubtedly once connected with it above sea level are the Channel Islands—Anacapa, which has been set apart as a National Monument—Santa Cruz, Santa Rosa, and San Miguel, named in order from east to west. Farther east and rising very abruptly above the plains are the San Gabriel Mountains which extend as far as Cajon Pass where the San Bernardino Range, the second high member of the Transverse system starts. The southern front of the San Gabriel Mountains forms the northern boundary of San Fernando, San Gabriel, and Santa Ana valleys, all of which lie to the west of Cajon Pass.

The *Ventura district*, about 70 miles northwest of Los Angeles, is chiefly hilly and mountainous. It is comprised of a number of sections, the highlands being the Santa Ynez Range, an east-west trending chain on the north side; the Sulphur Mountain Upland, a discontinuous highland in the central part formed by Sulphur, Red, and Rincon mountains; and the Coastal Hills, a low hilly region adjacent to the coast and extending inland parallel to the Santa Clara River east of Santa Paula. The chief lowlands are the Ojai Basin between the Santa Ynez Mountains and the Sulphur Mountain Upland, the Ventura River Valley, and the Santa Clara Valley along the south boundary of the district.

In the area is a nearly complete record of Cenozoic history of coastal southern California, for an immense thickness of deposits, about 47,000 feet, were accumulated partly when the land lay below sea level and partly when it stood above. The latest of the sediments belong to the uppermost Pleistocene, the earliest go back to the Eocene. During the middle part of Pleistocene time, the entire mass was folded and faulted, then was beveled off with the evolution of a rather advanced landscape. Still later, differential vertical uplift has invigorated the streams, developing the present erosion cycle.

The older landscape, best preserved on the summit of Sulphur Mountain, is called the Sulphur Mountain erosion surface. It was characterized by broad valleys with hills and low mountains rising

above. Because in most places later erosion has destroyed this landscape, its character has to be inferred from such remnants as are left.

Part of the present drainage pattern of the district is inherited from the Sulphur Mountain cycle, but part is recently initiated. Most of the recent changes have been accomplished by headward erosion and by diversion or capture of east-west streams by southward flowing streams. As a result, a few large through-flowing streams have courses roughly at right angles to the fold and fault trends of the area.

This east-west range rises about 6,000 feet, making a prominent barrier along the north side of the Ventura district. The streams of the southern part of this range are tributary to the Ventura River or to Santa Paula Creek. They flow down steep grades and have incised deep, narrow gorges into the mountain flanks. Since these principal tributaries flow nearly at right angles to the trend of the folds and faults, minor branches have excavated valleys into the weaker beds and hence parallel the structural trends. These lesser streams, having reached maturity, broadened their valleys and developed an almost continuous lowland paralleling the front of the Santa Ynez Mountains. This lowland, eroded in shale between two resistant sandstone ridges, shows most prominently north of Ojai Valley and west of the Ventura River in Kennedy Canyon.

The Ojai lowland is divisible into three parts, the Santa Ana Valley or western section, Long Valley in the center, and the eastern part which does not have a name. The Santa Ana Valley is principally a bedrock surface covered with thin residual soil, while in Long Valley, this bedrock is covered by river terraces. The eastern part of the Ojai lowland is filled with alluvium and at the eastern end are the two large alluvial fans of Sennor and Horn Canyons.

In the Santa Ana section, the two principal streams are Santa Ana and Coyote Creeks. The Santa Ana may have been inherited from the Sulphur Mountain erosion cycle, but its present valley was started during the period of uplift initiating the late erosion cycle during which the Sulphur Mountain surface has been largely cut to pieces. In an epoch of relative stability in the later cycle, the stream broadened its valley by the erosion of a wide terrace and then incised a narrow arroyo 50 feet deep below the terrace in consequence of a very recent uplift invigorating the power of the stream.

Coyote Creek was established later than Santa Ana Creek by headward erosion and diversion of east-flowing tributaries of the Santa Ana drainage.

East of Santa Ana Creek, the history of the valley is uncertain. The valley is divided into two nearly equal sections by a low ridge crossed both by Santa Ana and Coyote Creeks. The two halves of the valley

in the area east of the Santa Ana Creek may have been excavated by tributaries of the Ventura River when it flowed at a considerably higher level than at present.

The upper Ojai Valley is a small, lens-shaped basin about 5 miles long and 1 mile wide, ranging in altitude from 1,250 feet at the west to 1,550 feet at the east and separated from the main part of Ojai Valley by a ridge 50 to 150 feet high at the southern end and 300 to 500 feet high farther north. Westward the same ridge rises to 1,035 feet at Lion Mountain. The difference in elevation between the two parts of Ojai Valley probably results from erosion by San Antonio Creek along the eastern part of the Santa Ana fault which crosses the northern base of the dividing ridge. Because the south side of the fault has moved upward bringing resistant and less resistant rocks in contact, erosion has been slower on the southern, more resistant side, which now stands higher.

This nearly continuous ridge, convex to the south, runs through the center of the Ventura district and is breached by only two streams, the Ventura River and Santa Paula Creek. It consists of Sulphur Mountain east of the Ventura River and Red and Rincon mountains to the west.

The conspicuous feature of Sulphur Mountain is the sharp contrast between the advanced mature landscape of the summit, the elevated erosion surface of earlier time, and the bold southern face. Some have interpreted this declivity as a fault scarp, but actually it has been evolved by rapid stream removal of easily eroded shale.

Red Mountain, west of the Ventura River, is an elongate dome. In the weak rocks exposed during erosion of the dome, valleys have been evolved parallel to the structure and are separated by ridges of more resistant strata. These valleys are tributary to the drainage flowing down the slopes of the dome. Such a circular or elliptical valley and ridge pattern is often called *race-track* or *annular topography*.

On the summit of Red Mountain are numerous undrained depressions formed by movement of masses of sandstone down the slope. The hollows range from 100 to 400 feet long and 20 to 60 feet deep. Many contain permanent ponds while others are partly filled or converted to grassy flats. Most of the undrained hollows are at the east end of the mountain north of a large, now inactive slide at the head of Cañada del Diablo. A large slide in Padre Juan Canyon has projected the amphitheater-shaped head of this valley through the original crest, so that its stream is now attacking the north side of the mountain where it has beheaded several northward flowing streams.

As is common, the slide blocks have rotated backward as they have moved, and the undrained depressions lie between the rotated blocks and the scar left on the hillside as the masses broke away.

Rincon Mountain resembles Sulphur Mountain in its general topographic form and much of its geology. The crest is a rounded ridge falling off abruptly to the north and south, but rising gradually eastward to the domelike summit overlooking Los Sauces Creek. This rounded crest is a remnant of the Sulphur Mountain erosion surface and is the most prominent feature in the coastal area, standing 2,165 feet above sea level. On the south side of Rincon Mountain are 9 levels of marine terraces, the highest being between 1,250 and 1,300 feet above sea level. The terraces have been warped in process of elevation and increase in altitude eastward. All of the terrace surfaces are buried by later detritus which obscures a thin layer of older fossiliferous marine sand and gravel overlying wave-cut platform.

The Coastal Hills include the area between Sulphur Mountain and the Santa Clara Valley and inland from the coast to the eastern boundary of the region. The hills range in elevation from 1,000 to 1,950 feet. The Sulphur Mountain erosion surface undoubtedly extended across this section, but has been almost completely destroyed, being replaced by a hill and valley topography.

Landslides are abundant and even more so are masses of debris called earthflows that were water-logged when they started to slide. The landslides have moved down favorable surfaces of resistant strata while earthflows have occurred generally throughout the hilly belt.

The Ventura River flows from the Santa Ynez Mountains for 12 miles before entering the Pacific Ocean a mile west of the city of Ventura. It has a narrow flood plain in no place reaching a mile in width and in few places more than half a mile. In the lower part of its course the river meanders slightly, but in most places has an anastomosing channel, especially north of Ojai Valley. The last 2 miles of the valley seem to be underlain by deep alluvium, indicating that there was excavation in this section probably when the sea stood lower during the glacial stages of Pleistocene time.

Along the Ventura River are terraces which provide important information regarding the extent and nature of deformation since erosion of the Sulphur Mountain surface. The highest terrace stands at 1,180 feet on the west end of Sulphur Mountain where it merges with the Sulphur Mountain erosion surface, indicating that the Ventura River had evolved before the late Pleistocene uplift while the erosion of Sulphur Mountain surface was going on. The river probably established its course by headward growth and capture of an earlier drainage system, much as Santa Paula Creek has done in diverting west-flowing drainage of the upper Ojai Valley.

Deepening of the Ventura Valley kept pace with uplift, going on most actively when elevation was most vigorous. Then during episodes of greater stability, the valley widened out by the development of a lower terrace. This process has been repeated giving a succession of

terraces. As the deformation progressed, the terraces were bent into a broad arch which reached its maximum elevation at the Red Mountain fault.

Marine Terraces

At the base of the modern sea cliffs along the coast, there is a low wave-cut platform. Elevated terraces are restricted to two sections, the first extending from Pitas Point 7 miles west to the Carpinteria Plain and the second from Ventura east to the Santa Clara River. West of Pitas Point, terraces are prominent and best developed on Rincon Mountain where they have been recognized as high as 1,300 feet above sea level. Elsewhere their number and altitude are difficult to ascertain. Near Rincon Mountain the terraces have been tilted so that they slope toward the Carpinteria Plain; almost all of them have been cut by faults which produce small offsets in their surfaces, these reaching a maximum of about 30 feet.

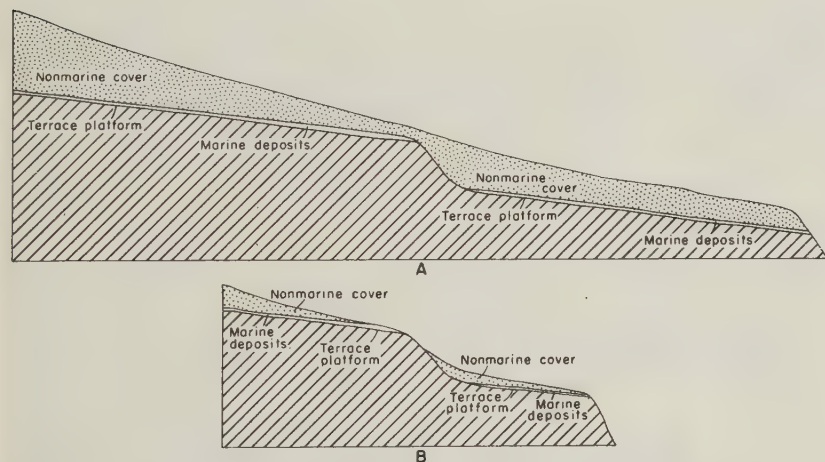


FIG. 132. Wave-cut terraces covered by veneer of marine deposits and then buried or partially buried by nonmarine cover of sediment after elevation of the terraces. A, Nonmarine cover concealing cliff between successive terraces. B, Nonmarine cover over terraces but not concealing cliff between them. *After U. S. Geological Survey.*

Behind Ventura, marine terraces have been eroded but are difficult to recognize because the bedrock and the terrace gravels are quite similar. Terrace form is best preserved on the lower ones and virtually disappears above 500 feet; evidence for their presence above this elevation is principally gravel remnants which may or may not be correctly identified as having been formed on a wave-cut surface. The best preserved terraces near Ventura are on the ridge immediately east of the Ventura flood plain. Practically the entire business district

of Ventura is built on the lowest one which stands 15 to 20 feet above the ocean and measures about 2,100 feet wide. Eight feet above sea level there is a second conspicuous bench at the east margin of the Ventura River Valley, but farther east this and the lower one are largely buried by an alluvial fan which has formed at the mouth of the first canyon west of Hall Canyon.

At 350 or 400 feet above sea level is the flattened ridge, also a marine terrace, on which stands the Serra Cross. Between this and a lower terrace at 200 feet, conspicuously shown near a large excavation behind the Ventura County Courthouse, are four minor ones indicating that the emergence of the land was broken by intervals of relative stability, some longer, as that when the main terraces were cut, and others shorter, such as those responsible for the lesser notches. As the land was elevated, there was some fracturing with displacements of a few feet showing in some of the terraces.

The evolution of the present shore line has been controlled by the direction of prevailing winds and currents and by inequalities in the resistance of rocks under attack by the waves. The unsymmetrical major headlands have a long northern side and are separated by short northeast-trending embayments. The sea breezes are generally strongest in the summer when the Santa Clara and Ventura valleys connect highly heated inland with the coast. Ocean currents flow eastward as a result; the waves associated with them parallel the longer stretches of the beach and approach the shorter side of each headland obliquely, the angle between the headland shore and wave front being between 20 and 30 degrees. Active erosion goes on along those parts of the shore attacked by this oblique wave approach.

Between Rincon Point and the Ventura River, the beach is a thin veneer of sand with bedrock cropping out for considerable distances. The widest beach is at Pierpont Bay southeast of the Ventura River, a shallow embayment between the Ventura and Santa Clara Rivers supplied with sand principally by the Ventura River. The beach is not being built outward, the shoreline in places standing as much as 2,500 feet from the base of the seacliffs, a result of the northward migration of the Santa Clara River over its flood and delta plain.

The last event in the history of this section of the coast has been slight emergence, shown by a wave-cut terrace exposed along the highway north of Pitas Point, where it stands 15 to 16 feet above sea level; this increases to 21 feet a mile and a half southeast of Seacliff station showing that tilting has occurred during emergence. Projection of the terrace landward beneath the cover of non-marine debris deposited on it indicates an elevation of about 45 feet at the base of the former sea cliffs which are 115 to 120 feet high. The terrace remnant is about 300 feet across at Pitas Point but increases to 1,200 feet at Seacliff station.



FIG. 133. The San Gabriel Mountains near San Dimas. *Photo by Spence Air Photos.*

The San Gabriel and San Bernardino Mountains are of about equal size and form an imposing barrier extending many miles north and east of Pasadena and Glendale. Both ranges are composed of a series of faulted blocks thrust upward from a region of rather low relief and elevated to their present height during Pleistocene time.

The southern front of the San Gabriel Range is a bold, considerably dissected slope marked by a complex system of faults whose base forms a sharp but irregular line separating the low alluvial plain to the south from the mountain block. West of San Antonio Canyon near Claremont and south of east-west Tujunga and San Gabriel Canyons, the summits of the range are from 3,000 to 6,000 feet in elevation, while north of this area, they rise to 8,000 and 10,000 feet, the highest point being Mount San Antonio or Old Baldy (10,080 feet). The ridges of this portion of the Transverse Ranges are sharp and the canyons deep, hence there are few remnants of the advanced landscape which was elevated as this fault block rose.

Like the San Gabriel, the San Bernardino Mountains are about 60 miles long in an east-west direction; they widen from a point at the summit of Cajon Pass (elevation 4,250 feet) to nearly 30 miles at their eastern end. The crest line of the western section is remarkably even and forms the drainage divide between the Mojave desert, which is part of the Basin-and-Range Province, and the coast. The crest begins near the summit of Cajon Pass at an elevation of about 5,000 feet and rises gradually for about 25 miles to the southeast where it reaches 7,500 feet above sea level. Then it is broken by Bear Creek Canyon. Beyond this narrow gorge, which is more than 3,000 feet deep, the crest again rises for more than 12 miles to 9,500 feet, but is no longer the drainage divide; it culminates in Sugarloaf Mountain, 9,500 feet high. Southeast of the Santa Ana River into which Bear Creek empties, the range is most rugged and reaches its highest elevation, with San Gorgonio Peak, 11,485 feet above sea level, as its supreme summit.

In the vicinity of San Bernardino, the south front of the San Bernardino Mountains is a steep, battered fault scarp that faces the Santa Ana valley and makes a clearly defined straight boundary with this alluvial plain.

The summit region to the north of the crestline referred to above is a gently rolling plateau whose high points do not rise more than 1,500 feet above the bottoms of the valleys between them. The plateau is a remnant of the same advanced erosion surface that is much more damaged by later erosion in the San Gabriel Mountains. Prior to the uplift of these blocks, this flat surface seems to have occupied a large part of southern California, though its limits cannot be determined because of the great amount of later deformation. The features of this older topography in the San Bernardino Mountains are sharply contrasted with the much more rugged topography developed as the range

has been rising. This new landscape consists of deep narrow canyons which are eating headward into the plateau and gradually destroying it. Between the recently cut gorges are sharp crested, narrow ridges. The western part of the plateau drains into the Mojave River and the eastern part into the Santa Ana River.

There appear to be two principal fracture belts on the southern side of the San Gabriel section along which this mass has risen, one lying at the foot of the range and the other somewhat farther back within it. The fault system along the front of the mountains is called the Sierra Madre; the total displacement which has occurred along this fracture zone is probably about 5,000 feet, judging by the position of the bedrock floor at the base of the range and the elevation at the top of the scarp. East of Dalton Canyon, this fault zone diverges from the range front and runs along the base of foothills south of the main scarp; this section is called the Cucamonga fault, along which displacement ranges from a few feet to 1,000 feet west of San Antonio Canyon.

The fault zone within the range is called the San Gabriel; north of it, the range rises in elevation nearly 3,000 feet, a change that may be due to movements along the fault.

Other fractures that have caused less displacement include the San Andreas, which cuts the San Gabriel Range near its northeast margin, and has moved horizontally.

Most of the southwest margin of the San Bernardino Mountains is bounded by the great San Andreas fault, the major fracture system in California. The several faults that diverge from the San Andreas zone, swinging eastward into the range, are probably responsible for most of the uplift along the south and west sides. The western San Bernardino Mountains appear to be a succession of fault blocks, each tilted to the north.

North of the San Andreas zone, five important faults run eastward into the range and appear to have been the zones along which the southwestern part of the mass has been elevated.

The cumulative effect of the uplift which has taken place along the east-west faults in the San Bernardino Mountains is partly offset by the tilting of the blocks northward as they have risen. However, the old erosion surface, represented by the even crest line, is 5,000 to 7,000 feet above the bedrock south of the San Andreas fault where the same surface shows.

The Santa Monica Mountains that start about 5 miles northwest of the City of Los Angeles and the four Santa Barbara Islands—Anacapa, Santa Cruz, Santa Rosa, and San Miguel—in the not very distant past were a continuous chain. The islands which are smaller units have been isolated by crustal movements while the main mass, the Santa Monica Mountains, is locked to the land by the Ventura Basin which



FIG. 134. Deep, narrow canyons eroded in the San Gabriel Mountains of southern California. The barrenness of the slopes allows speedy runoff of heavy rains and consequent torrential floods which sweep through the gorges. *Photo courtesy U. S. Army Air Corps.*



FIG. 135. San Geronio Peak, high point (11,485 feet) in the San Bernardino Range, a member of the Transverse group. Rivers have cut deep canyons into the range, extensively destroying an erosion surface of relatively gentle relief which extended across the mountain block prior to its uplift. *Photo by Fairchild Aerial Surveys.*



FIG. 136. Santa Monica Mountains (background), the slightly dissected Santa Monica alluvial plain (foreground), and sea cliffs now being cut into the plain (left foreground). *Photo by Spence Air Photos.*

abuts against them on the northern side. Several kinds of evidence, particularly elephant remains in Pleistocene rocks on the Santa Barbara Islands comparable with types found in rocks of the same age on the mainland, indicate strongly that the chain was formerly connected. The islands, an east-trending group, are now separated by deep submarine troughs, a plan characteristic of the rather broad continental shelf offshore from the Los Angeles Basin. Studies suggest that the varied contour of the shelf in this section, which contrasts with the normal rather smooth seaward slope, has resulted from faulting which developed a number of small, nearly rectangular blocks which have moved upward and downward, giving a rather heterogeneous arrangement of islands, submarine basins, and higher standing underwater areas. This faulting is assigned to the late part of Pleistocene time.

The Santa Monica Range is about 45 miles long, has an average width of 10 to 15 miles, and rises from 1,000 to 3,000 feet above sea level, the higher parts being in the western section. The western 30 miles front on the Pacific Ocean, where strong wave erosion has developed a prominent sea cliff 175 to 200 feet high. Highway 101 runs along the base of this cliff and Highway 27 crosses the mountains from Topanga Beach west of Santa Monica.

The eastern part of the Santa Monica Mountains has quite subdued contours, making them a hilly rather than a mountainous belt. The crests of the hills rise 1,300 to 2,100 feet above sea level or 800 to 1,500 feet above the adjacent plains. There is some increase in elevation westward. The crest of the mountains is a series of flat-topped ridges of about the same elevation. The flat tops appear to be remnants of an old erosion surface which transgressed the Miocene strata of the earlier Santa Monica anticline. This advanced landscape, probably belonging to old age of the erosion cycle, seems to have been developed in the earlier part of Pleistocene time after a vigorous deformation in the later part of the Pliocene epoch. During the later part of the Pleistocene, the surface has been brought to its present elevation and has been materially dissected by streams.

Some of the streams, like those in Topanga and other major southward directed canyons, are fed by springs and therefore permanent; the rest flow only during the heavier rains. The Los Angeles River, major stream of the area, flows from the Simi Hills and Santa Susana Mountains across the San Fernando Valley and around the eastern end of the Santa Monica Mountains. Generally dry, the drainage system often carries wild torrents during heavy rains.

The main drainage divide of the Santa Monica Mountains lies near the northern side and not in the central part as might be expected. This very likely results from the higher elevation of the plain to the north against the base of the mountains and the longer distance which the streams must flow to reach their lowest level of erosion.

Although the Santa Monica Mountains, particularly the eastern part, are relatively subdued in contour and remarkably uniform in elevation over considerable areas, yet there are some higher and more abrupt topographic features which appear to have been caused by late faulting. The Vicente Mountain area west of upper Sepulveda Canyon and a wedge-shaped, fault-bounded granite mass west of upper Laurel Canyon are examples. It also seems probable that the steep granite front of the mountains north and west of Hollywood has resulted from comparatively recent movements along the Hollywood fault, which were terminated on the west at the north end of the Newport-Inglewood uplift near Beverly Hills. Farther west this deformation was not by faulting but by uplift and tilting of a wide Pleistocene alluvial plain. Except for local faulting, the Santa Monica Mountains seem to have been elevated as a unit in the late part of the Pleistocene epoch.

The alluvial plain just mentioned is called the Santa Monica Plain; it lies north of the city of Santa Monica and extends east and west along the base of the mountains. The plain was formed by streams flowing southward from the Santa Monica Mountains during Pleistocene time, depositing much of their load before reaching the ocean. Later on wave erosion has cut the plain back toward the mountains, materially reducing the distance which the streams had to travel before reaching the coast and causing them to cut deep trenches into the plain. In some of the deep canyons north and northwest of Santa Monica, like lower Santa Monica and Temescal, stream terraces are well developed, four being recognizable though not with equal ease. The uppermost terrace stands about 50 feet below the surface of the Santa Monica Plain and from 250 to 265 feet above sea level. In Rustic Canyon, probably the same terrace, again 50 feet below the level of the Santa Monica Plain, is 400 to 425 feet above the ocean.

About the middle of the magnificent stretch of sea cliffs terminating the Santa Monica Mountains along most of their southern side is a promontory of basaltic rock called Point Dume (pronounced Dumé) which projects about a mile into the ocean beyond the rest of the shoreline. There, protected from erosion by Point Dume, is a small stretch of weak Tertiary rocks. Preserved in this area are two marine terraces, one about 100 feet and the other about 200 feet above present sea level. A third terrace level is forming at the base of the cliffs along the coast. The elevated terraces indicate two uplifts followed by two episodes of quiescence during which the waves indented the land; since the last deformation there has been relative stability allowing the formation of the present cliffs and terrace.

This valley is a rudely triangular plain about 20 miles long in an east-west direction; its width at the western end is about 3 miles and at the eastern end about 10 miles. The Los Angeles River rises at the western end of the plain, flowing to the east along its southern side

and out through hills at the extreme southeast corner. Almost all of the valley is a center of active deposition. The eastern half is covered by the highly pervious fans made largely of granitic gravel which have been deposited by Big and Little Tujunga Rivers and Pacoima Creek; the western half is covered by less pervious cones of smaller streams draining from adjacent hills which are composed largely of sedimentary rocks.

Beyond the coast, the Channel Islands, including Anacapa, Santa Cruz, Santa Rosa, and San Miguel, extend far enough westward so that San Miguel lies due south of Point Conception east of Santa Barbara but is separated from it by about 30 miles of ocean. These islands evidently were once part of the Santa Monica Mountains, westernmost member of the Transverse Ranges, and have been separated by the deformations which have profoundly affected this part of the California coast in quite late time. To the southeast are Catalina, San Clemente, San Nicolas, and Santa Barbara islands, not part of the first group, but all members of the little galaxy collectively called the Channel Islands.

San Clemente, typical of the Channel Islands, lies about 50 miles south of the Palos Verdes Hills, the nearest point on the mainland. The Palos Verdes Hills themselves were once an island but have been annexed to the mainland by sedimentation. Between Catalina and San Clemente is a 25-mile stretch of ocean. San Clemente is about 21 miles long, 4 miles in maximum width, narrowing to about 1 mile at its northwestern end. The greatest elevation, 1,964 feet, lies just a little east of the center of the island. From the crest, the descent on the northern side is very abrupt, dropping in one place 1,800 feet in half a mile. The southern slope is more gradual, broken principally by a remarkable series of elevated marine terraces. The bold northern face is broken here and there by deep gorges.

San Clemente is a simple tilted fault block not greatly modified by erosion, the northern side therefore being a somewhat battered fault

scarp. The contrast in slope between the northern and southern side is continued below sea level, for 2 miles from the northern shore depths of 3,600 feet have been measured, as near Wilson's Cove, while at the same distance from the coast on the opposite side, the water is only 300 feet deep.

There are minor faults paralleling the trend of the boundary system, and low scarps have been observed along them.

The outstanding features of the landscape, developed largely on the southern side are marine terraces, which are described as outstanding for their size, continuity, and distinctness.

As high as 1,320 feet above sea level, the terraces are so well preserved that they can be traced for miles; more than 20 have been recognized. It is evident that the deformation which caused the elevation of San Clemente to its present height was interrupted by times of relative quiescence during which the terraces and sea cliffs behind them were evolved.

REFERENCES

- Bailey, T. L., Late Pleistocene Coast Range orogenesis in southern California: *Geol. Soc. America Bull.*, vol. 54, pp. 1549-1568, 1943.
- Davis, W. M., Glacial epochs of the Santa Monica Mountains, California: *Geol. Soc. America Bull.*, vol. 44, pp. 1041-1133, 1933.
- Eckis, Rollin, South coastal basin investigation: geology and water storage of valley fill: California Div. Water Resources Bull. 45, 1934.
- Hoots, H. W., Geology of the eastern part of the Santa Monica Mountains, Los Angeles County, California: U. S. Geol. Survey Prof. Paper 165-C, 1930.
- Miller, W. J., Geomorphology of the southwestern San Gabriel Mountains of California: *Univ. California Dept. Geol. Sci. Bull.*, vol. 17, pp. 193-240, 1928.
- Putnam, W. C., Geology of the Ventura region, California: *Geol. Soc. America Bull.*, vol. 53, pp. 691-754, 1942.
- Putnam, W. C., and Bailey, T. L., Geomorphology of the Ventura region, California: *Geol. Soc. America Bull.*, vol. 53, pp. 691-754, 1942.
- Reed, R. D., and Hollister, J. S., Structural evolution of southern California: *Am. Assoc. Petroleum Geologists Bull.*, vol. 20, pp. 1529-1704, 1936.
- Russell, R. J., Land forms of San Geronio Pass, southern California: *Univ. California Pub. in Geography*, vol. 6, pp. 23-121, 1932.

PENINSULAR RANGES

PENINSULAR RANGES

The southwestern corner of California is occupied, except for a belt of marine terraces along the coast, by mountainous land which has been called the Peninsular Ranges. This great highland extends from the vicinity of Los Angeles and Riverside nearly to San Fernando at about latitude 30° in Lower California, a distance of nearly 300 miles with two-thirds of it being south of the Mexican border. North of the ranges lies the Transverse Ranges Province; at the southern end is the desert of San Borja. The average width of the Peninsular system is about 50 miles; on the California side of the border it includes the Santa Ana Mountains which are detached from the main body.

The eastern side of the province is strikingly defined, for there a great eroded scarp descends abruptly from a more subdued upland landscape to the floor of the Imperial-Coachella graben which nowhere in the state stands more than a few hundred feet above sea level. With few exceptions the highest elevations in the Peninsular Ranges are located close to this scarp while the western side slopes much more gradually. In California the highest point is Mount San Jacinto (10,508 feet), a short distance west of Palm Springs. Santa Rosa Mountain farther to the southeast rises 8,046 feet above sea level.

Viewed as a whole, the Peninsular Ranges are a gigantic fault block which has been raised with tilting upward on the eastern side like the Sierra Nevada. Actually, however, this block is divided into minor units along subsidiary fractures which either lie parallel to the boundary system or at high angles thereto. Each block has had a more or less distinct landscape evolution which has depended upon the nature and magnitude of movements affecting it. The great eastern scarp, simple in places and in others developed by intersecting faults, along the front of the San Jacinto and Santa Rosa sections is comparable in majesty with that of the Sierra Nevada fronting on Owens Valley; it is especially conspicuous west and south of Palm Springs. At this city, the elevation is 445 feet above sea level, while San Jacinto Mountain, a little more than 7 miles distant is more than 10,000 feet higher. For a thousand feet above the Coachella Valley, this scarp rises abruptly above which there is a considerable reduction in slope. This indicates recency of movement elevating a block which had advanced to greater age in the scheme of landscape evolution, and this is further proved by the fact that the scarp is notched by comparatively few deep canyons which have at their mouths only small alluvial fans. Although the scarp apparently does not have the actual slope of the boundary fault system, it has not receded very far. South of the San Jacinto-Santa Rosa mass, this boundary declivity, while prominent, is in most places not so high or steep.

The Peninsular Range resembles the Sierra Nevada also in distribution of precipitation, most falling over the broad western slope. The dominant winds come from the ocean, rise over the highland, and lose most of their moisture before reaching its crest.

Descending the eastern slope, the air is warmed, absorbs moisture most of the time, and the climate becomes increasingly arid toward the base of the range where it adjoins the desert Imperial-Coachella basin. On the western side rain and snow are much less than at equivalent elevations over most of the Sierra Nevada. The broad western slope of the great Peninsular block together with the distribution of precipitation has caused the development of numerous though not very large streams flowing toward the Pacific Ocean. Because of the abrupt descent of the eastern scarp and the less moisture available, the streams are short and small; they very quickly disappear after reaching the mouths of their canyons by evaporation and by sinking of their water into the highly pervious alluvial fans. Only the larger floods transport debris beyond the margins of the fans onto the flatter floor of the desert basin.

Above the scarp the change in landscape is conspicuous, for much of the range shows an advanced topography into which the western slope streams have eroded gorges and canyons 500 to more than 1,500 feet deep. In places this upland is gently rolling, in others hills or mountains of irregular pattern rise above its general level, erosion residuals which had not been worn away before the great block began to rise in recent time. Also particularly near the eastern scarp, there are short detached summit ranges, some oriented parallel to the trend of the range but most directed more nearly east-west. In California the more prominent of these isolated ranges are the San Jacinto west of Palm Springs, the Agua Caliente and Cuyamaca farther south; beyond the Mexican border there is the culminating range of San Pedro Martir and at the southern extremity of the Peninsular block, the Sierra San Juan de Dios. In the western part, this broad seaward slope increases from about 1,500 feet in elevation to more than 3,500 feet as in Cowles, San Miguel, and Otay mountains. It rises to more than 4,000 feet in McCains Plateau and over 6,000 feet in the Laguna Mountains along the eastern escarpment. The increase in elevation is by no means gradual or uniform, for the range has been fractured into large and small blocks which have moved more or less independently of each other. Many of these blocks stand out as moderately well defined plateau areas, while others, less uplifted and usually smaller form basins or valleys and valles as they are called. Some of these dislocated remnants of a once continuous erosion surface have been little affected by the stream invigoration which has accompanied ele-

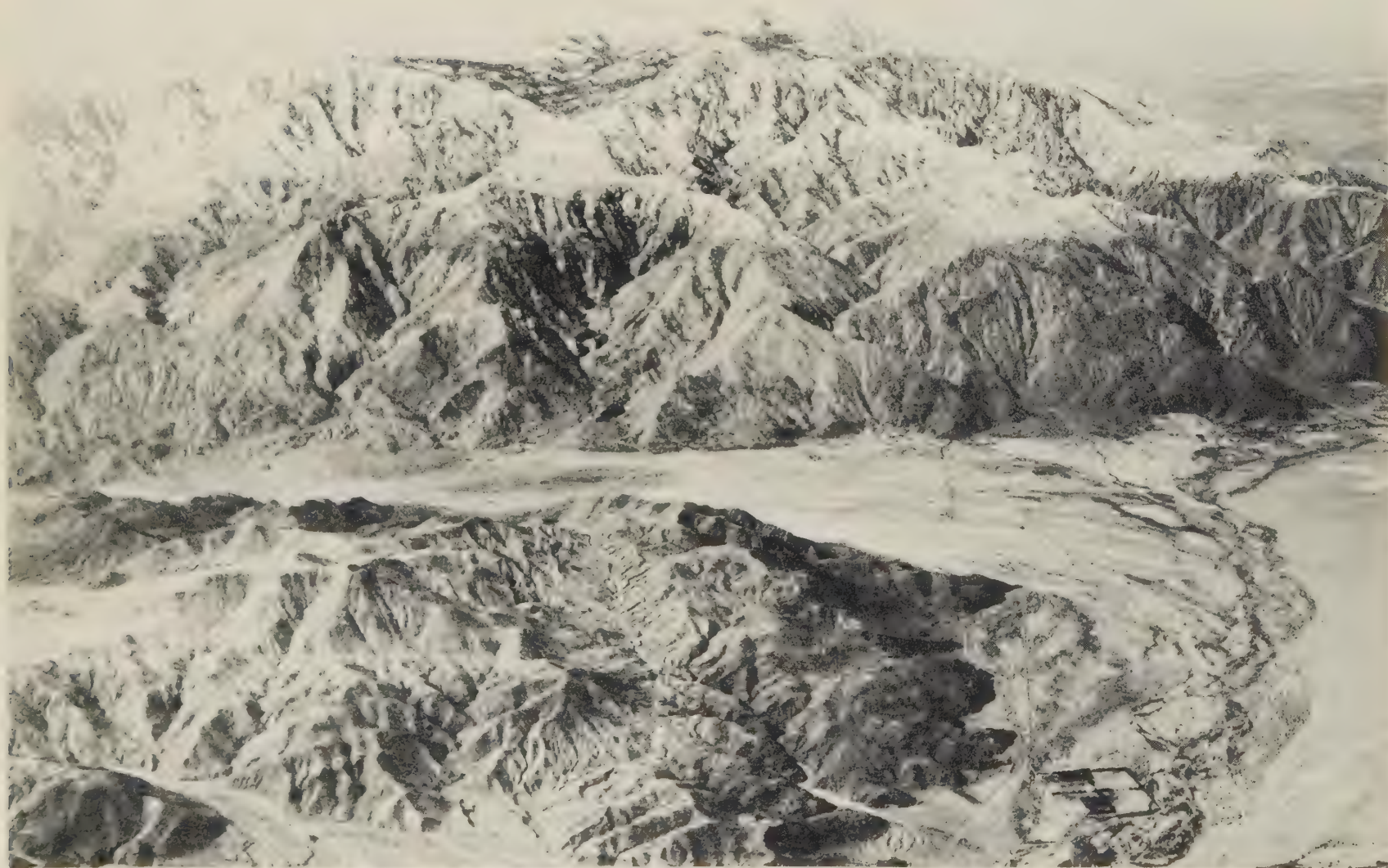


FIG. 137. San Jacinto Range near Palm Springs, California. This part of the range has been elevated by recent movements along faults and is broken by a number of large active faults within the block. At the mouth of the canyon at the base of the high block is an alluvial deposit brought from the range by flood waters of the stream. The eastern margin of the Imperial Valley graben (Coachella section) shows along the lower righthand side. The culmination peak, Mt. San Jacinto, rises more than 10,000 feet above sea level; the floor of the Imperial Valley at Palm Springs is about 400 feet above sea level. *Photo by Fairchild Aerial Surveys.*

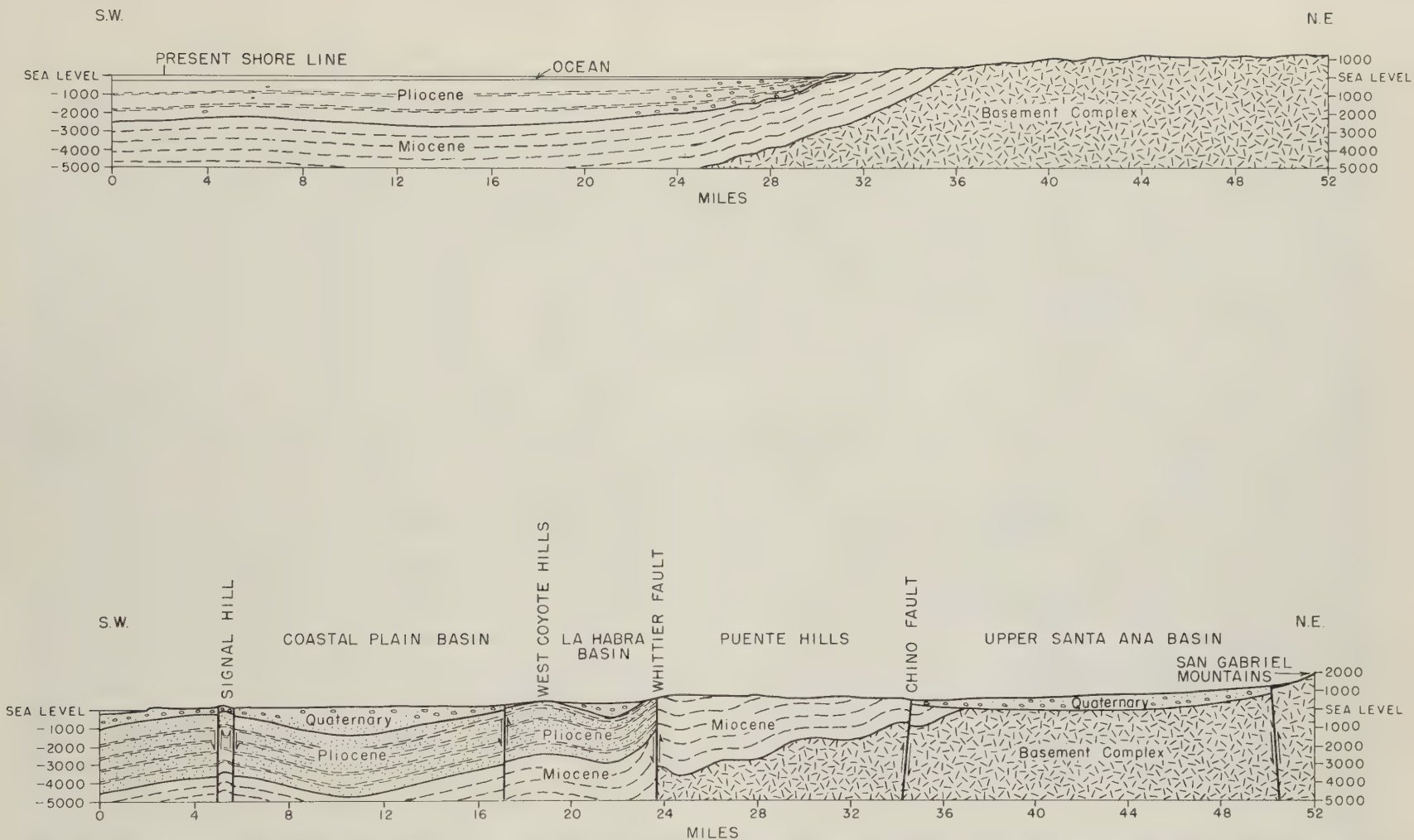


FIG. 138. Top, diagrammatic section across the south coastal basin, showing the probable late Pliocene basin of distribution when that part of the area was below shallow ocean water. *After Rollin Eckis.* Bottom, diagrammatic section along the same line, showing the Pleistocene (Quaternary) basins of deposition when the area was mostly above sea level. *After Rollin Eckis.*

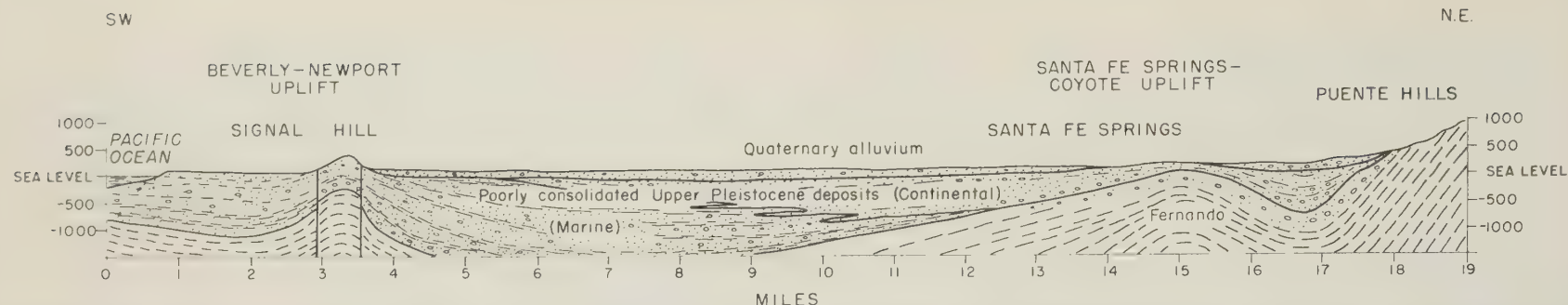


FIG. 139. Diagrammatic section across the Santa Fe Springs-Coyote and Beverly-Newport uplifts. The Quaternary alluvium is very late Pleistocene. *After Rollin Eckis.*

vation of the Peninsular Range. Examples of these little damaged remnants may be seen south of Alpine at 2,000 feet, south and southwest of Guatay Mountain at 4,000 feet, and the rather large area of the McCains Plateau between Jacumba and La Posta valleys also at about 4,000 feet. Below this advanced erosion surface lies deep residual soil and weathered but still coherent rock through which project masses of much fresher material.

The old landscape had been evolved by long erosion prior to elevation of the range. It seems to be similar in its topography and may once have been continuous with that in the uplands of the San Bernardino and San Gabriel Mountains, and in many remnants scattered through the Mojave Desert. This surface has not been studied in much detail hence its history is not well known. Whether it exhibits the multiple features so finely shown on the western side of the Sierra Nevada has not been determined, but such evidences of recurrent uplift and associated dissection are to be expected.

In the Peninsular Range there is a considerable number of basins; one of the largest is the Valle San Jose between Palomar, Volcan, and Agua Caliente mountains whose crests rise from 2,500 to 3,500 feet above a flattish floor of considerable extent. Others are Viejas, Cottonwood, and Morena valleys. Some of the basin floors exhibit the ancient landscape little modified by erosion while others have stood sufficiently low relative to their surroundings so that they have received considerable deposits of alluvium or have harbored lakes in which sediment accumulated. Field study indicates that these basins actually are grabens which either sank as the Peninsular block was being elevated or failed to rise as far as their surroundings. Thus they are features comparable to those found in the Sierra Nevada (Tahoe and Sierra basins and various others), to be expected in a great mass which is being elevated along major faults. The deformation of such a block

is complex and it yields to the deforming forces by bending and minor fracturing, the latter finding more expression in relief features than the former.

At various places in the range there are a number of long, narrow depressions which appear to have resulted from erosion in the crushed zone of larger faults.

The recency of uplift of the Peninsular block is testified to by the boldness and small amount of erosion of the eastern scarp and the depth and narrowness of canyons cutting both it and the western slope. Some have held that the great eastern face is an erosion product, though its evolution by this mechanism has not been very clearly brought out. However, comparison of its features with those of the eastern face of the Sierra Nevada and the clear evidence of a major fracture system along the base of the Peninsular block indicate beyond much doubt that this scarp is the product of great dislocations which have caused elevation of the range and sinking of the adjacent Imperial-Coachella graben. The eastern Peninsular scarp is highest and most abrupt at the northern end. Farther south in places there is a series of parallel northwest trending mountainous ridges, clearly fault-block mountains, between which are sharply outlined sunken blocks like Collins, Borego, and Clark Lake valleys. The Santa Rosa Mountains is the principal of these ridges, with a long, straight scarp a few thousand feet high on the southwest side, above which there is a slope (the old erosion surface) descending to the northeast from 8,000 to about 6,000 feet above sea level. Beyond is the great eastern scarp. In other places the eastern front is less simple indicating parallel faulting with distribution of the dislocation along the various fractures giving step-fault topography.

Between the northernmost part of the San Jacinto section of the Peninsular Range and the San Bernardino section of the Transverse



FIG. 140. San Jacinto section of the Peninsular Ranges west of Palm Springs, showing abrupt front which is controlled by recent elevation along faults. Discontinuous alluvial fans at mouths of canyons in the range and the relatively flat floor of the Coachella section of the Imperial Valley graben make the foreground. *Photo by Fairchild Aerial Surveys.*



FIG. 141. Marine terrace and recently eroded sea cliff along Palos Verdes Hills, a one time island which has been joined to the shore. *Photo by Fairchild Aerial Surveys.*

system is San Gorgonio Pass whose crest is about 2,600 feet above sea level. High points on the ranges immediately adjacent rise from 8,000 to 9,000 feet. From its summit, the pass slopes gently eastward where it merges imperceptibly with the northern end of the Coachella valley. On the western side, the slope is quite as gentle toward the Beaumont Plain, but the margin between the pass and this plain, while not prominent, is more conspicuous than that on the eastern side. The main part of the San Gorgonio depression is a lowland 2 to 3 miles wide and about 18 miles long; it is a narrow fault trough or graben filled to a great depth with sediment of quite recent deposition. Bedrock comparable with that exposed in the adjacent San Jacinto and San Bernardino ranges therefore must stand a considerable distance below the surface of the trough.

The southern boundary of San Gorgonio Pass is the spectacular, battered fault scarp of the San Jacinto Range. At the eastern end of the pass, the sheer mountain front bends from east-west to more nearly north-south, and in this angle lies the famous desert resort of Palm Springs. The northern margin of the pass is not so conspicuous, partly because the high peaks of the San Bernardino Range lie farther from its base than those of the San Jacinto Mountains and partly because of a foothill belt which lies between the pass and the former range. In the narrow fault trough between the two ranges there has been greater deposition of sediment from the northern range than from the southern, hence the northern side of the pass stands 300 to 500 feet higher than the southern.

Although the San Andreas fault passes diagonally along the foothill belt of the San Bernardino Range, other faults are responsible for the difference in elevation between the pass and the summit of the mountains. The Banning fault makes a group of scarps along the northern side of San Gorgonio Pass, some of the movements being so late that they have tilted recently formed alluvial fans.

Wind blowing over sedimentary deposits in the pass have swept sand into drifts that are found on both windward and leeward sides of ridges projecting from the San Jacinto Mountains. Excellent examples of sand blasting, the erosive effect of the wind, are found near some of the drifts.

Roughly paralleling the southern California coast and lying about 20 miles inland are the Santa Ana Mountains which run for some distance southeast of the Santa Ana River. The mountains are a fault block of rather complex structure which has been elevated on the northeastern side along the great Elsinore fault system and tilted southwestward toward the ocean. The crest, lying along the northeast side of the block, is rather uneven, increases in elevation southeast from the Santa Ana River, and culminates in Santiago Peak (elevation 5,680 feet). On the northeastern side of the block, the range front is a steep, battered fault scarp, drained by short streams that

run into Temescal Wash at its base. In contrast, to the southwest of the crest, long ridges slope toward the ocean. Santiago Creek is the principal stream on this side and drains practically all of it.

The Santa Ana Mountains, like the nearby San Gabriel and San Bernardino ranges, have been uplifted during Pleistocene time. The Elsinore fault along which the uplift has occurred is an extremely complex system, no single fault running continuously through the entire length of the zone.

The northern side of the range is terminated by the Whittier fault which runs westward from the Elsinore zone. Northeast of the Santa Ana River, this mountainous belt is continued by the Puente Hills. The Puente Hills are relatively low and inconspicuous as compared with the Santa Ana block.

The Palos Verdes Hills are an isolated upland peninsula projecting into the ocean along the western side of the south Coastal Plain west of the city of Long Beach. The general features of this upland resemble those of the islands off the coast of southern California and it is evident that during parts of Pleistocene time it, too, was separated from the mainland. Northwest of the Palos Verdes Hills a belt of irregular sand dunes extends inland from the coast, overlapping the lowland and the northwestern border of the hills.

The peninsula is small, measuring about $9\frac{1}{2}$ miles long and 4 to 5 miles wide; its highest point, San Pedro Hill, stands only 1,480 feet above sea level. The crest and most of the upper slopes of the area are a rolling upland comprised of smoothly rounded hills and wide, gently sloping valleys. Along the lower slopes is a series of marine terraces which are being indented by deep canyons that are working inland and gradually destroying the rolling upland. The west and south coasts of the peninsula terminate in a sea cliff ranging from 50 feet high at Long Point to 200 feet at Malaga Cove and 300 feet at Bluff Cove. It averages between 100 and 150 feet. Along the east coast at the city of San Pedro, the cliff is about 50 feet high.

The Palos Verdes Hills form a conspicuous uplift along the coast where deformation during the late Pliocene, middle Pleistocene, and late Pleistocene can be recognized. The boundary between the hills and lowland is thought to be a fault, but such does not show at the surface. However, this northern boundary has been the most mobile section of the entire Palos Verdes area. The strata composing the hills have been thrown into mostly broad, gentle folds, though in a few places they are steeply dipping and locally overturned.

The rolling upland is believed to be part of an old erosion surface developed over a much wider area before the isolation of the Palos Verdes Hills as an island. It is characterized by widely flaring valleys separated by round crested ridges, the maximum relief preserved being about 700 feet. These valleys are sharply contrasted with the narrow gorges advancing into the lower slopes from the shoreline.

When the upland topography was evolved cannot be exactly determined, but probably it had been completed by early or middle Pleistocene time.

A number of undrained depressions are present in the upland area, being most numerous at the northwest end. They are thought to have been formed by solution of parts of the thin limestone beds that are known to underlie the area with consequent settling of overlying strata into the voids which were left, though drainage changes also may be responsible for some of them.

The most striking features of the Palos Verdes Hills are the elevated marine terraces of which 13 have been recognized. The terraces range in height above sea level from about 100 to 1,300 feet. The gentle slopes on San Pedro Hill above an altitude of 1,425 feet may represent a still higher terrace formed when the island was completely submerged, but this has not yet been proved. The lower and therefore younger terraces naturally are best preserved and most easily identified; they are most clearly visible on the windward west coast and the southwest coast from San Pedro Hill to Point Fermin where they have been eroded into the most resistant rock. Between the two areas the continuity is broken by erosion of the steep slope and by landsliding. On the leeward slopes where waves cut into weak rock, terraces are exceptionally wide, but, where the rock is more resistant, the weaker wave action developed less well-defined terraces. In places the terraces appear to merge, probably because of accumulation of non-marine debris after emergence. Locally this non-marine cover is at least 100 feet thick. In some places it seems to have spread onto still lower terraces concealing the sea cliffs between. The height of sea cliffs between the different terraces is not uniform, but actually measurement is not possible because of later erosion and deposition.

The terraces indicate that the elevation of the Palos Verdes Hills followed the normal pattern, taking place more rapidly during certain intervals and then perhaps almost ceasing for a time. The cutting of the terraces occurred during the episodes of stability.

Along the northern border of the Palos Verdes Hills the lowest terrace was deformed following emergence and deposition of the non-marine cover. Along most of the west coast and almost all the south coast, the lowest elevated terrace has been destroyed by erosion developing the present terrace at sea level. The valley now occupied by Gaffey Street in San Pedro was cut across the warped lower terrace by an antecedent stream or by a stream which breached the Gaffey anticline, running through this section, and captured a stream formerly draining southeastward north of the anticline. It seems probable that recent slight growth of the Gaffey anticline has caused impounding of the water of Bixby slough north of the anticline.

There are numerous landslides at various places. One extensive area forms the hummocky area inland from Portuguese Point and

Inspiration Point and is explained by movement along a slipping plane formed by a water-soaked bed of tuff.* A large slump of different type took place in 1929 about a quarter of a mile east of Point Fermin. A semi-elliptical area extending for 1,000 feet along the sea cliff and 400 feet inland moved seaward as a body, leaving a main fissure 5 to 10 feet wide in an irregularly fissured zone 50 to 100 feet wide. This slide was attributed to sliding on the slippery surface of a shale bed inclined seaward in an anticlinal fold. Soon after it was formed the main fissure was filled with fossiliferous marine sand from Second and Beacon Streets. Movement took place again in 1940 suggesting that the slumped mass rotated upward as it moved toward the ocean. Exceptionally heavy rains in 1941 caused the slide to become active again indicating that stability has not yet been reached.

San Gabriel Valley

This plain, like the San Fernando, is about 20 miles long, 7 to 10 miles wide for most of its length, but narrows to little more than 2 miles at its eastern end. The gentle slope of its surface is to the south. Rising abruptly to the north are the high San Gabriel Mountains.

The debris cone being formed by the San Gabriel River occupies the central part of the valley extending from the mouth of the mountain canyon across the plain and through the Whittier Narrows to the Coastal Plain. This area of active deposition is extended east and west of the cone by accumulations of smaller streams coming from the San Gabriel Mountains. Dissected older alluvium covers most of the east and west parts of the valley and is found elsewhere, and its soil zone is reddish-brown, whereas this coloration is not present in areas of active deposition. Uplift of the San Gabriel Mountains has been responsible for dissection of the cones on that side of the valley where there are many high remnants of old cones fringing the mountain front between the canyon mouths. The head of San Dimas cone which covers the floor of the narrow eastern part of the valley has been cut by streams to a depth of 125 feet. Toward the central part of San Gabriel Valley, this older dissected surface gradually merges into the surface where deposition is going on.

Steep-sided bedrock hills project here and there through the alluvium and contrast strikingly with the general topography of the valley. All are near the sides of the valley and around them the alluvial deposits are comparatively thin. Wells in the central part of the valley show a thickness of 1,000 to at least 2,000 feet for the alluvial fill; this can only be accounted for by substantial subsidence of the bedrock, since the deposits extend more than a thousand feet below sea level.

At the east end of the San Gabriel Valley in the vicinity of La Verne, the alluvial plain narrows to a width of about 2 miles and then widens

* Tuff is a volcanic rock made of small fragments of lava developed during volcanic explosions.

into the upper Santa Ana Valley, which is about 40 miles long from west to east. The width of its western part is about 20 miles, and decreases almost to a point at the eastern end. Under the comparatively even surface of the valley is an irregular bedrock floor covered in places by more than 1,000 feet of alluvium which has come principally from the San Gabriel and San Bernardino mountains.

The greater part of the upper Santa Ana Valley is covered with undissected, recently deposited alluvium, but around the margins, particularly the southern, and at places farther within the basin there are eroded remnants of higher deposition surfaces with their characteristic reddish-brown soil zones.

The Santa Ana River, below the San Jacinto fault at San Bernardino, has cut through the older alluvial deposits to depths of 50 to 100 feet and flows on a narrow flood plain which it has formed between these high banks. The river lies south of the present area of active accumulation of sediment from the San Gabriel Mountains. The two facts just presented suggest that the central part of the Santa Ana Valley has been recently subsiding.

The Coastal Plain extends along the ocean south of the Santa Monica Mountains for about 50 miles and extends inland for 12 to 20 miles. Except for the San Pedro Hills, which are an isolated group rising about 1,500 feet above sea level near the coast line, the plain has a relatively even surface broken here and there by low hills and mesas. The eastern part has been built up from the shallow sea floor during relatively late Pleistocene times by deposits which streams have brought from the interior, whereas the western part is rather recently uplifted and only slightly modified continental shelf. Below lie thick deposits of Pliocene and Miocene age formed when the region stood mostly below sea level.

It has been shown that oscillations of sea level together with deformation of the earth have at times left certain parts of the plain well above the present level of deposition while other sections have been submerged below this level. The uplifted areas stand as hills, terraces, or mesas which have weathered, usually red or brown soil surfaces and are now undergoing erosion. In the parts which have been sinking, alluvial debris is actively accumulating and the surface is covered by relatively unweathered sandy or silty soil.

The most conspicuous of these dissected areas are two rows of hills which have been produced by recent folding and faulting of the plain. The first is the Beverly-Newport uplift, a hilly belt extending southeast from Beverly Hills to Newport Beach and including the Baldwin Hills at Inglewood, Dominguez Hills, Signal Hill, Landing Hill, Huntington Beach Mesa, and Costa Mesa. The second row of hills begins at Santa Fe Springs south of Whittier where it is scarcely visible and ends in the Coyote Hills several miles to the east.

West of the Beverly-Newport uplift, streams have cut into the Coastal Plain to depths of 25 to 100 feet; between the valleys are broad, flat, mesa- or terrace-remnants of a marine surface uplifted in late Pleistocene time. This surface extends from the base of the hills to the coast where it ends abruptly in a series of bluffs. At its northern end this marine surface is contemporaneous with the deeply eroded surface of alluvial cones along the base of the Santa Monica Mountains.

Between San Pedro Hills and Santa Monica is a series of old sand ridges which in part at least were offshore bars built up from the ocean floor when this section was below sea level. These sand bar ridges appear to have provided sand which has formed dunes covering a considerable area south of Inglewood. If this explanation is correct, the bars in the Inglewood area have been so modified by the removal of sand that their original form is unrecognizable.

At certain localities on the lower parts of the old marine surface referred to above there has been some deposition of products removed from higher areas, but in general there has been little covering by later sediment since the continental shelf rose above the ocean.

Streams eroding the western part of the Coastal Plain flow through moderately broad alluvial plains covering mature valleys eroded below the level of the old marine surface. These plains stand little above sea level and the streams empty into sloughs with marshy tidalands. Because the sloughs indicate subsidence, it seems probable that the western part of the Coastal Plain stood somewhat higher above sea level than it does today, and that the streams now flowing over flood plains traveled through broadened gorges now filled with delta and delta plain deposits laid down as a rising ocean invaded the mouths of the gorges.

The Beverly-Newport uplift makes an important break in the Coastal Plain even though its relief is not considerable. The Pleistocene sea bottom making the surface of most of the western Coastal Plain is faulted and folded up over this row of hills and then slopes down on their eastern side where it passes below very late Pleistocene stream deposits. East of the Beverly-Newport barrier, the surface of the Coastal Plain is an undissected surface underlain by stream deposits which extends from the base of the Santa Monica Mountains to the vicinity of Irvine. At the two ends this alluvial surface is narrow, but in the middle it is about 15 miles across.

This unbroken alluvium is the surface of a great trough into which three principal rivers, the Los Angeles, San Gabriel, and Santa Ana and various minor streams are pouring debris. Well logs show that the stream deposits form a thin veneer below which are at least 1,500 feet of marine sediments laid down when the area was below sea level during the later part of the Pleistocene epoch. The thinness of the stream-laid beds indicates that filling above sea level has occurred in very late time.

The low hills running from Santa Fe Springs to Coyote Wash have separated a narrow depression, generally known as La Habra Basin, lying north of the hills from the main Coastal Plain. This basin therefore has been filled with stream sediment as it gradually rose while most of the main Coastal Plain was below sea level and was receiving sediment deposited in the ocean.

Older stream deposits, folded up over the Santa Fe Springs-Coyote uplift, stand above the level of deposition on the central Coastal Plain. This older alluvium has been dissected and weathering has developed a reddish-brown soil zone in its upper part.

Elsewhere between the principal rivers, dissected alluvial cones with weathered-reddish brown soil zones fringe the north, east, and south margins of the Coastal Plain. The surfaces of these dissected cones, steeper at their apexes than the present streams, converge with them toward the center of the Coastal Plain and finally pass beneath the streams.

Considerably dissected remnants of old marine terraces, which include erosion terraces together with beach and inner continental shelf deposits, are found along the coast beyond both the northwest and southeast ends of the Coastal Plain. Along the southwest side of the Palo Verde Hills they are especially well-developed, seven or eight well-defined old shore lines and others less distinct having been recognized. The highest terraces remnants stands more than 1,000 feet above the present shore line, but they are not very distinct because of damage which erosion has wrought since their elevation.

This portion of California extends from the Pacific shoreline to the Peninsular Ranges east of the city of San Diego and can be divided into two sections, the coastal mesas which are part of the south Coastal Plain and the rugged mountainous section rising abruptly on the eastern boundary of the mesas. The two parts are composed of quite different rocks and have had quite distinct histories.

The mesa section has a semi-arid climate, the precipitation being about 10 inches annually at San Diego and not much greater at the base of the mountains. Most of the rainfall comes between October and April. The temperatures normally have moderate range, freezing being rare in the winter and oppressively hot days equally so in the summer. The mountainous section on the other hand receives considerably more rain and snow in the higher parts during the winter. Summer days in some of the valleys have temperatures reaching 100°F. and more. The higher peaks and ridges cause speedy condensation of the eastward drifting air currents as they rise along them, giving precipitation of more than 40 inches a year on the western slopes of such ranges as the Palomar and Cuyamacas. Within the mountains precipitation decreases somewhat in most places but exceeds 20 inches annually.

The mesa section extends for many miles north and south of the San Diego region; on the north it is continuous with the south Coastal Plain of the Los Angeles Basin while on the south it passes beyond the Mexican border. The mesas either extend to the coast where they are cut off by cliffs being eroded along the present coast or descend by a series of terraces which are separated by bays or a coastal plain from the shoreline. In width the mesa section ranges from 6 to 14 miles and in height from sea level to more than 800 feet. The most conspicuous mesa which is nearly flat-topped and only slightly dissected stands at elevations ranging from 300 to 550 feet.

The coast line within this area has two promontories, a broad northern one formed by the mass of Soledad Mountain near La Jolla and a southern at the isolated, north trending Point Loma. There are two embayments, a smaller one, Mission Bay or False Bay as it was formerly called, between Soledad Mountain and Point Loma, and the larger and deeper San Diego Bay which is protected by Point Loma and a long sand spit called the Silver Strand, Coronado and North Island.

The eastern boundary of the mesa section is determined by the abutment of Tertiary sediments against much older rocks forming the foothills of the mountains to the east, though this boundary is rather indefinite in places where the Tertiary sediments thin out to a veneer of soil upon the older formations.

The mesas are terraces cut by wave action and covered by a thin veneer of rather coarse marine deposits; there are several of these terraces, the higher being much dissected and less easily identified. The principal terrace is called the San Diego, below which are others developed on the western margin of this mesa. The lower terraces are of comparatively small area, but are quite distinct where they have not been destroyed by later erosion.

The San Diego Mesa has been trenched by streams from the mountains into a number of sections to which various local names are applied. The name Otay is used south of Otay Valley and Linda Vista Mesa or Terrace north of the San Diego River. Southward the mesa was elevated higher and more rapidly than to the north, for near the Mexican border, its surface stands about 550 feet above sea level while just south of the San Diego River, the elevation is little more than 300 feet.

The surface of the San Diego Mesa appears to be an almost featureless plain broken here and there by rather deep gorges cut by streams flowing from mountains to the west. Actually, however, there are many gentle undulations, such as long, low ridges which may have been beach ridges. Some doubtless have developed because of differences in weathering and erosion in various parts of the mesa. Also there are many small hillocks 3 feet or more high and having a basal



FIG. 142. Elevated marine terrace at Torrey Pines. A new terrace and sea cliff are being developed by waves along the present shore line. *Photo by Fairchild Aerial Surveys*



FIG. 143. The lower part of San Diego is built on slightly elevated wave-cut terraces. Beyond in the middle ground are the much broader and higher San Diego terraces. In the background are the Peninsular Ranges. *Photo by Spence Air Photos.*



FIG. 144. San Diego Harbor (Yacht Club Section) showing long hooked sand bar standing some distance off shore. Peninsular Ranges in background. *Photo by Spence Air Photos.*

diameter of 10 to 20 feet, called *prairie mounds*. It is thought that these small eminences may represent both the accumulation of sand about and the irregular removal of sand between bushes or other clumps of vegetation. Since the hillocks are present not only over the top of the mesa but along its marginal slope, the probability is that they were formed as the land rose and the ocean cut terraces below the San Diego level. During such an epoch, there probably was plenty of available sand which the wind drifted inland and piled wherever an obstacle was present.

The beach ridges previously referred to are numerous north of the San Diego River where they have caused the partial development of a trellis drainage by the streams eroding Tecolote Canyon and smaller canyons east of La Jolla. Elsewhere in the mesa section the drainage is the normal dendritic or treelike type. The beach ridges are composed largely of sand which either shows poor stratification or none at all.

The San Diego Mesa is but little damaged by stream erosion and therefore is in the youthful stage. The northern portion, especially the section immediately adjacent to the south rim of Mesa Valley and Linda Vista terrace to the north is less dissected than the part to the south, probably because of the harder rock in the Linda Vista area and the closer spacing of valleys south of Choyas Valley.

Many of the canyons cutting the mesa have quite steep slopes and their tops meet the mesa surface in a sharp angle.

The San Diego Mesa probably is also represented by parts of the upper surface of Point Loma though faulting in that area has tilted some of the remnants, and also by a much less evident surface about half-way up the southern and western slopes of Soledad Mountain where again tilting has occurred.

The western sides of the San Diego Mesa and the sides of some of the larger valleys exhibit well-preserved remnants of lower, younger terraces, of which there are four principal levels and others much less well developed. The principal ones are the Avondale, standing 200 to 250 feet above sea level; the Chula Vista (100 to 130 feet); the Nestor (25 to 100 feet); the Tia Juana (20 to 50 feet). Southward from Otay Valley these terraces, like the San Diego Mesa, stand at progressively higher elevations and are separated by greater vertical distances. Since the terraces represent surfaces of marine erosion covered by a thin veneer of deposits, it is evident that uplift has been greater and more rapid toward the Mexican border than farther north. All of the terraces are probably younger than middle Pleistocene; they testify to dominant vertical elevation in the San Diego region while farther north there was considerable compressional deformation during the same epoch.

In the older rocks of the Peninsular Range east of the coastal mesa belt, remnants of a much older surface can be distinguished clearly

which has been called the Poway Terrace because of its conspicuous development in the hilltops south of Poway Valley. East of Linda Vista Mesa it can be seen at the tops of hills 800 to 900 feet above sea level at the west but sloping upward to elevations of 1,100 to 2,100 feet 5 to 20 miles eastward. The terrace was not developed by wave action, as were those previously described, but represents a surface evolved principally by rivers which had reached advanced maturity or possibly old age. Many eminences rose above the general level, but it is uncertain which of these were developed by erosion and which by faulting.

The same surface is preserved in parts of the upper drainage basin of the San Diego River as a rolling upland only partly destroyed by canyons evolved during a late cycle of uplift. Also in parts of the region around Potrero and extending with interruptions far to the east of Carpo and for an unknown distance into Lower California, there is an ancient erosion surface which may well be the equivalent of that just described.

Some have considered this elevated surface as an ancient, much dissected and warped marine terrace evolved during the Eocene epoch, but it seems much more probable that it was a surface developed above sea level primarily by rivers not earlier than Pliocene time.

Differences in geologic structure and rock resistance have caused various irregularities in the shoreline of the San Diego region. Resistant masses of rock form promontories because waves cannot so easily destroy them as they can weaker materials. The embayments or coves between the headlands have been partially filled by streams emptying into them and by sand driven in by waves. North of La Jolla, the San Diego Mesa has been quite evenly attacked by wave erosion with the formation of a long stretch of cliffs at the base of which there is a narrow beach. The land appears to be sinking slowly so that during storms the waves are able to attack the base of the cliffs, undercutting them with resultant landslides. In this section the rate of cliff retreat is fairly rapid.

About a mile south of Scripps Institute near La Jolla, where there is a mass of resistant rock, the coast projects about a mile into the ocean. Because of differences in resistance of various parts of the rock to erosion, waves have sculptured caves, small arches, and irregular stacks. A few feet above high tide is a narrow bench or terrace which some have believed to represent recent uplift; on the other hand it may be the product of erosion during especially severe storms. South of La Jolla the coast is irregular for about 3 miles to the beginning of Pacific Beach, where weaker rocks and other factors have made easier wave erosion. In this section is a terrace upon which the community of Pacific Beach is located. Debris evolved in erosion of this terrace and also that brought in by streams has been shifted southward by

waves and coastwise currents to be deposited almost completely across the mouth of Mission Bay which was formerly known as False Bay and by the Spanish as Puerto Falso. A long spit with a narrow tidal opening at the south is called Mission Beach.

Mission Bay appears to be a structural depression, which may be the southern downwarped part of Soledad Mountain. Mission Bay is very shallow and is being gradually filled by the encroaching delta plain of the San Diego River. Intermittent streams from various canyons also are adding to this deposit.

A broad point, known as Bay or Crown Point, is an extension of La Jolla Terrace projecting into Mission Bay from Pacific Beach. Its surface is largely covered with windblown sand. When the sea cut the Crown Point section of La Jolla Terrace, it must have swept up the low ground between Mission Bay and San Diego Bay isolating Point Loma as an island.

The low flat land between Old Town and the northeast margin of Point Loma is part of the delta plain of the San Diego River. As the delta plain has grown, the river and its tributaries have occupied many different positions in traversing it, as is shown by earlier maps of the area. Like most streams in this region, the San Diego River has infrequent floods, but when they come a large amount of sediment is brought down to be added to the delta plain and the submarine delta section to the seaward. Some shoals and small islands have been formed in Mission Bay by tidal currents and waves.

Point Loma is a long promontory extending from the tidal flats of Mission Bay for 6 miles southward, where it landlocks the western portion of San Diego Bay. This peninsula is about 3 miles wide at the north, narrows to a little more than a mile and a half at the south and stands about 300 feet above sea level. Its flattish top is possibly the equivalent of the San Diego Mesa, from which it may have been isolated by subsidence of the land round about in late Pleistocene time. Parts of the eastern and western side of Point Loma have a narrow terrace standing 25 or more feet above sea level. The western shoreline is quite irregular owing to variations in resistance of the rocks.

San Diego Bay is a long, roughly crescentic, landlocked arm of the ocean with which it is connected by a narrow channel on the east side of Point Loma. The south and southwestern shore of the bay consists of North and South islands and a sand spit connecting them and attaching both to the mainland. The two islands may be remnants of the Nestor Terrace (elevation in this part of the San Diego region about 25 feet), but their connection with the mainland resulted from the construction of a long crescentic sand spit by the northward drifting of debris brought to the sea by the Tia Juana River which enters the ocean near the Mexican border. Spanish Bight is a small, shallow re-entrant of San Diego Bay between North Island and Coronado.

San Diego Bay is relatively shallow except where dredging has maintained a navigable channel. Tidal scour at the entrance has been aided by the building of a jetty which may eventually have important effect upon wave and current action along Coronado and South Island. Shortly after it was built, violent storm waves eroded a large part of Ocean Boulevard west of Hotel del Coronado. A small stone jetty or breakwater was constructed southeast of the hotel in 1897 and 1898 to protect it from wave erosion, and a sea-wall of quarry stone was built westward along Ocean Boulevard in 1906 and 1907, and was repaired in 1911 and 1912 because of heavy damage by storm waves.

The mainland shore of San Diego Bay is mainly salt marshes and tidal flats except where the Nestor terrace produces a small bluff just above high tide line. Intermittent streams from Las Choyas, Sweet-water, and Otay Valleys have constructed small, marshy delta plains.

There is no delta at the mouth of Tia Juana River which flows into the ocean south of San Diego Bay near the Mexican border because waves and currents sweeping along the shore remove debris about as fast as it was deposited.

The Nestor Terrace is continuous from the foot of San Diego Mesa—or Otay Mesa as it is called on some maps—westward to the beach north of the mouth of Tia Juana River, except for a little swale extending from Tia Juana Valley northwestward to the southern end of San Diego Bay. This drainage depression crosses the highway just west of Nestor and Palm City, and appears to represent erosion by overflow of former great floods which swept down Tia Juana Valley.

Most of the valleys crossing the mesa have flattish floors above which rock walls rise very abruptly for 300 or more feet; they have been eroded into relatively weak sediment by streams rising in the mountains to the east. Only Otay Valley has a rounded bottom and may be younger than the rest. The flat floors have been evolved by the filling of gorges with alluvium that extends below present sea level. It is probable that during the lowered oceans of the glacial stages, the streams cut their valleys through the weak material to meet the falling shoreline. Then, as the sea has risen, the valleys have been gradually filled in by sediment. Measurements indicate that some of the alluvial fills which started as deltas and rose above sea level as delta plains extend at least 120 feet below the present surface of the ocean.

In the mountains east of the mesas, the streams flow in deep, narrow, young canyons evidently eroded as these ranges have risen to their present height in the very late part of earth history. In fact, the mountainous mass is still being elevated.

Faulting has broken up the mountainous mass so that actually it is a series of blocks which have been elevated to various extents, though there is a general increase in height from the foothills on the west to the high crest peaks on the east; this increase in elevation however,



FIG. 145.—San Diego Mesa, at San Diego, principal member of a terrace flight extending from the shore to the base of the Peninsular Ranges. The mesa have been tilted during elevation so that the one in the photograph rises from about 300 feet at its northern end to about 550 feet along the Mexican border. *Photo by Fairchild Aerial Survey.*

is far from uniform. The Palomar Mountains, Volcan Mountain, the Laguna Mountains, and various other units appear to be fault blocks. In the western part of the Peninsular Ranges the trend of the principal faults appears to be roughly northeast-southwest corresponding to the trend in other parts of this highland. Rolling uplands already described are present in various parts of the mountains, but whether they are parts of a single erosion surface or of various erosion surfaces has yet to be determined.

In a region where deformation has produced such profound changes in the landscape during late geological time, movements are still going on in various sections, perhaps in all parts. Topographic features produced by movements along faults have already been described and many of these show along the active faults of the state. What is not so generally known is that certain areas are slowly rising or sinking. Evidence of this has been described along the sea coast, but we are inclined to associate this with the past and not think of it as going on today. In the Los Angeles section, instrumental surveys have shown that certain parts either are being elevated or are being depressed so rapidly that surveys made a few years or even a few months apart show vertical movement has gone on. As a basis for the surveys, mean sea level, whose position is determined by some federal agency such as the U. S. Coast and Geodetic Survey or the U. S. Geological Survey, is used. A brief summary of some of these unstable areas follows to give the reader a picture of the reality of deformation which probably goes on everywhere at all times though in most places at rates too slow to be determined.

One of the sinking areas includes a large part of the Beverly Hills and some adjacent territory to the east and south, perhaps 15 square miles in all. The maximum rate of subsidence centers approximately at the intersection of Melrose Avenue and La Cienega Boulevard where it amounts to about one five-hundredths of a foot per year, at least from 1925 to 1937. While this is unusually high, the effect would not be noticeable in a good many years. Surveys made in 1929 and repeated in 1937 showed that part of Venice and of Playa del Rey also had sunk ninety-six hundredths of a foot in the 12 years, with the maximum at the intersection of Forty-second Avenue and Trolley-way in the southern part of Venice.

In contrast, west of Inglewood there is a rising area in which the detected movement has been about three hundredths of a foot a year. This appears to be actual elevation and not merely relative to subsidences taking place east and west. This rising area is adjacent to a fault zone which extends from the south base of the Santa Monica Mountains near Beverly Hills southeast beyond Inglewood as far as Signal Hill north of Long Beach. As horizontal movement takes place along the fault, which apparently runs through strong rocks at some depths, the sedimentary beds overlying the fault bend

into small anticlines which are arranged en echelon. Eight oil fields are located on or close to this deformation zone—Beverly, Inglewood, Potrero, Rosecrans, Dominguez, Long Beach, Seal Beach, and Huntington Beach. Small hills such as Dominguez Hill and Signal Hill appear to be anticlines formed along this fracture zone which is called the Newport-Signal Hill uplift. The fault apparently is active for epicenters of several recent earthquakes are located along it.

From Inglewood eastward for several miles there is another subsiding area.

In the Los Angeles and Long Beach Harbor areas changes of level noticed by engineers appear to be upward and downward in periods of about 7 months. At Long Beach and the country round about evidence of rather rapid elevation and depression has been determined in the last 20 years. The low, marshy, lagoonal section between the Palos Verdes Hills and the low, rounded, but rather conspicuous hills along the Newport-Inglewood uplift appears to be subsiding. Stream, marsh, and beach deposits here are rather thick, indicating relative subsidence for much longer time than human history in the area probably includes. Before being interfered with by man, the Los Angeles River deposited enough sediment in this coastal area to offset the effect of sinking; otherwise there doubtless would have been a large embayment in the Los Angeles and Long Beach harbor areas. Along the eastern margin of this low area are the hills of the Newport-Inglewood uplift, the most conspicuous being Signal Hill near Long Beach. These hills are anticlines developed by deformation of sedimentary layers which overlie the fracture zone. Both Signal and Dominguez Hills have been proved to rise intermittently; earthquakes occurring along the Newport-Inglewood fault may control this upward movement. Between earthquakes when the crust is more stable, the hills seem to subside as does the area between them and the Palos Verdes Hills.

In Long Beach itself both elevation and subsidence have been determined, most of the movement being downward. Elevation occurred between 1930 and 1932, before the highly destructive earthquake centering along the Newport-Inglewood fault zone in 1933, and again between surveys made in 1940 and 1941. There was a moderate earthquake in 1941 and others later, but what effect these had on the movements is not known. Such scanty evidence as is now available suggests that uplift occurs prior to disturbance along the Newport-Inglewood zone, but this may be coincidental. Instruments which have been set up in the area may show definite relations when enough recordings have been made.

For the Long Beach area in general there appears to be elevation in the northern part and subsidence toward the southwest with an intermediate zone where no change of level has been recorded. Thus the area is being warped with tilting downward to the southwest.



FIG. 146. Oceanside, California. The city is built on a broad terrace. Mountains in the background are part of the Santa Ana Range. *Photo by Fairchild Aerial Surveys.*

Signal Hill has an independent subsidence area which includes the summit of this anticlinal dome. Between 1926 and 1931 it subsided nearly half a foot. Oil-field operations may be responsible for the sinking here and at Venice and Playa del Rey.

In 1941 the concrete foundations of a number of oil wells situated on Terminal Island in the Long Beach Harbor area showed evidence of subsidence at an extraordinarily rapid rate. The sinking apparently was local though in an area of slower depression. The shortening of a shallow superficial layer of sediment and high pumping rate from deep water-wells operated by the U. S. Navy in the prior month probably were contributing causes.

The causes of the elevation and depression are varied. Earth movements play a very important part and probably are responsible for most. Also the drying out and compaction of clay layers and other natural volume decreases in sedimentary rocks are a factor. In addition the works of man play a part—extraction of water, oil, and gas; drainage and deflection of water either already below the surface or that which would sink in were the artificial controls not used.

Such changes affect the surveying of the land for they may prevent establishment of much needed stations which do not change in eleva-

tion. In addition certain ones may damage drainage canals, sewers, drawbridges, and other structures and they have bearing on the behavior of oil in producing fields. Insignificant though the movements may appear to be and taking place very slowly in most cases, over long periods of time they can produce profound alterations in the earth's relief such as have been described.

REFERENCES

- Dudley, P. H., Geology of a portion of the Perris block, southern California: California Div. Mines Rept. 31, pp. 487-506, 1935.
- Eckis, Rollin, South coastal basin investigation—geology and ground water capacity of valley fill: California Div. Water Resources Bull. 45, 1934.
- Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, California: U. S. Geol. Survey Water-Supply Paper 446, 1919.
- Hertlein, L. G., and Grant, U. S. III, Geology and paleontology of the marine Pliocene of San Diego, California: San Diego Soc. Nat. Hist., vol. 2, 1944.
- Miller, W. J., Geomorphology of the southern Peninsular Range of California: Geol. Soc. America Bull., vol. 46, pp. 1535-1562, 1935.
- Russell, R. J., Land forms of San Geronio Pass, southern California: Univ. California Pub. in Geography, vol. 6, pp. 23-121, 1932.
- Sauer, Carl, Land forms in the Peninsular Range of California as developed about Warner's Hot Springs and Mesa Grande: Univ. California Pub. in Geography, Vol. 3, pp. 199-290, 1929.

SEA FLOOR

SEA FLOOR

Knowledge of the contour of the ocean floor has been greatly increased in recent time because of the development of instruments with which rapid determinations of depth can be made. Formerly depths had to be measured by weighted lines let down to the bottom, a time consuming process particularly in the deeper waters. Measurements obtained in this way were fairly numerous in places where navigation made them necessary but were widely scattered elsewhere, consequently our concept of submarine landscape was extremely sketchy. In the last two or three decades instruments called *fathometers* have been perfected which measure depth by reflection of sound waves from the sea bottom, a much more rapid method. In many places, especially in the shallow waters, the topography has been quite accurately worked out and good maps have been made of the suboceanic floor. In deeper waters, although depth measurements are still too few, they are numerous enough so that our concept of the relief has been materially revised.

Materials from the ocean floor are obtained by dredging and coring, but of course these operations can extend only to very shallow depths. A moderately complete knowledge of surface materials on the ocean floor has been obtained at shallow depths and even from the deep ocean, but nothing is known of what lies below. Most of the floor of the ocean is covered with sediment and the lower layers undoubtedly have been consolidated into rock. In a few places in shallow waters there are indications of the thickness of deposits but nothing is known for the deeper.

Practically everywhere around continental and island coasts there is the flattish *continental shelf* sloping gently out to sea from the shore line as much as a few tens to a few hundreds of miles. Beyond this is the *continental slope* which descends somewhat more or much more abruptly to the great depths of the ocean. However, off the southern California coast, the picture is quite unique for there is a series of ranges and basins extending for about 160 miles that is much more closely related in structure and topography to the land than to the deep ocean. The continental shelf is very narrow; beyond it is the zone of irregular topography termed the *continental borderland*. The normal landscape of the shelf is quite different from that of the land as the contours are much simpler; farther out in the ocean the basins extend deeper below their surroundings than basins on the land and the tops of mountains called submarine banks are much flatter.

Because of the basins in the continental borderland off the coast of southern California, withdrawal of the sea from this area would leave a group of large lakes, some up to 1,000 square miles in area, and comparable with many of those now existing within the continent.

In depth these imaginary water bodies could exceed any in the United States, the Santa Cruz Basin being 2,880 feet below its rim and the St. Nicholas basin 2,370 feet. Crater Lake in Oregon, deepest in North America is about 2,000 feet while the deepest spot in Lake Tahoe in the Sierra Nevada is more than 1,600 feet below the surface. On the other hand, there are basin not containing lakes deeper than any mentioned; for example, Saline Valley, which lies between Owens Lake and Death Valley, has its lowest outlet 3,900 feet above its base.

The area of the submarine basins off the coast of southern California is about 6,300 miles, approximately a fourth of the total extent of the continental borderland in that section. The basins are roughly elliptical and are elongated northwest and southeast. Submarine findings indicate that their walls are long, steep slopes broken by a few valleys, though there are abrupt changes in the direction of the walls

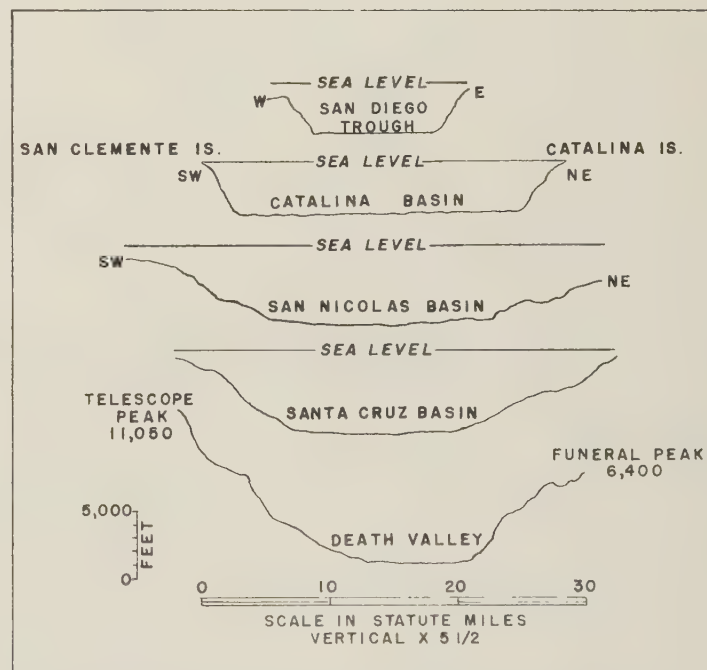


FIG. 147. Sections across the basins and troughs off the coast of southern California. Depths by U. S. Coast and Geodetic Survey and the E. W. Scripps Institute of Oceanography. After F. P. Shepard and K. O. Emery.

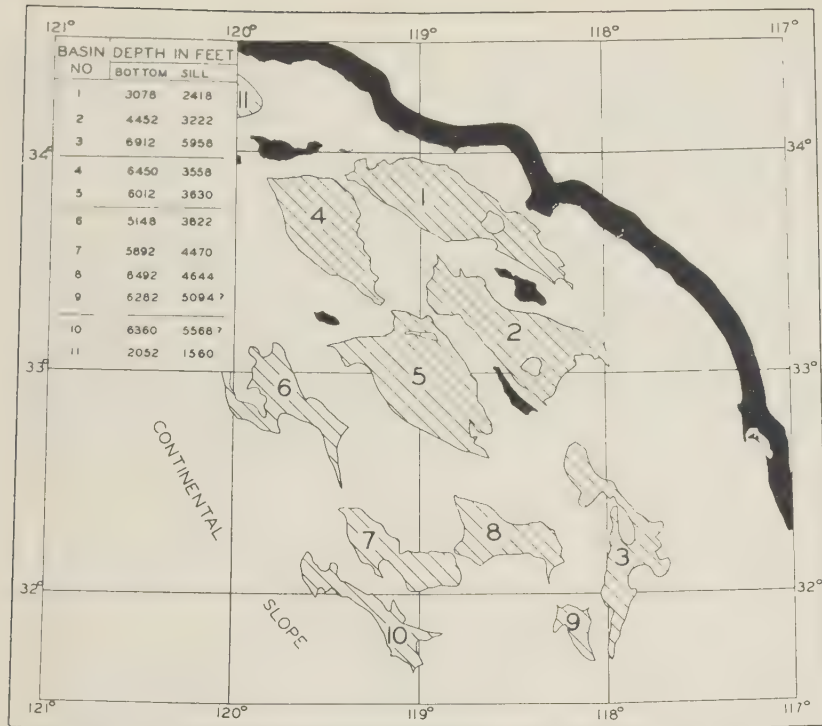


FIG. 148. Basins off the southern California coast which would hold lakes if the sea were withdrawn. After F. P. Shepard and K. O. Emery.

apparently controlled by folds or faults. Soundings taken across the basins indicate relatively flat floors broken by moderate irregularities.

The rims of the basins which would represent outlets of the lakes if the sea were withdrawn become deeper below sea level toward the southeast, and most of the basin floors deepen in the same direction. Such islands as are present rise from the northern part of the shelf. All of this suggests that there may have been downwarping in a southeasterly direction, a submergence which would account for the notable widening between the upper margin of the continental slope and the shore line which so sharply contrasts this region with the rest of the California borderland.

The relief of this borderland is diverse. At least one peak, probably conical in shape, is present southwest of the Coronados Islands and a few of the banks are elliptical in plan. Most of the eminences are long, relatively narrow ridges, small portions of some of them rising above sea level to form the islands off the southern California coast. The higher parts of the borderland are comparable in size to the short mountain ranges of the adjacent lands. The San Bernardino Ranges

rise about 9,000 feet above adjacent basins, while the submarine San Juan Seamount stands roughly 10,000 feet above neighboring flats. Santa Cruz Island has an elevation of about 9,000 feet above the floor of the Santa Cruz submarine basin, while Catalina Island compares with the Santa Ana Mountains, each about 6,000 feet above surrounding territory.

In contrast with the highly sculptured contours of the mountains above sea level, the submarine slopes even where steep in general are relatively smooth. However, there are exceptions, as for example the many small canyons in the bank on which San Nicolas Island is located, distinct valleys around Cortes and Tanner Banks, and one off Catalina Island. Even on the land, some mountains are much more intricately dissected than others.

Conspicuous features of this submarine region are the flattish tops characteristic of the submarine banks, features yet unexplained.

The sea floor in this southern California section compares with the adjacent land in showing more than one direction of trend of ridges, the prevailing being northwest-southeast, like those of the Santa Ana and San Jacinto mountains on the land. On the north, an east-west trend cuts across the other, probably a continuation of structures of the east-west Santa Ynez, Santa Monica, San Gabriel, and San Bernardino Ranges. Below sea level there is also a north-south trend, shown in a ridge southeast of San Clemente Island. This island together with Catalina and the Palos Verdes Hills on the land line up in a north-south direction. A few oval submerged areas are northeast-southwest and thus are at right angles to the dominant trend.

Many of the steep slopes in this borderland area in all probability are fault scarps, as for example off San Clemente, Catalina, and Coronados Islands and offshore from the Palos Verdes Hills which now are attached to the land but formerly were one of the islands.

The basin between Santa Catalina and San Clemente islands apparently is bounded by fault scarps and if so is a graben. There are certain complexities in the scarp on the San Clemente side which have not been explained.

In many places the trends of the submarine fault scarps are broken by offsets in fashion quite similar to that observed in scarps of like origin on the land.

Under the ocean marring the normal smoothness of the continental shelf and frequently extending far down the continental slope are deep, narrow gorges very closely simulating those eroded by rivers. That many of them are branching further increases the likeness. Some are confined largely to the continental slope into which they break to depths of many thousands of feet while others project back into the shelf, virtually to the shore line. Some are located offshore from the mouths of rivers running on the land while others do not have this

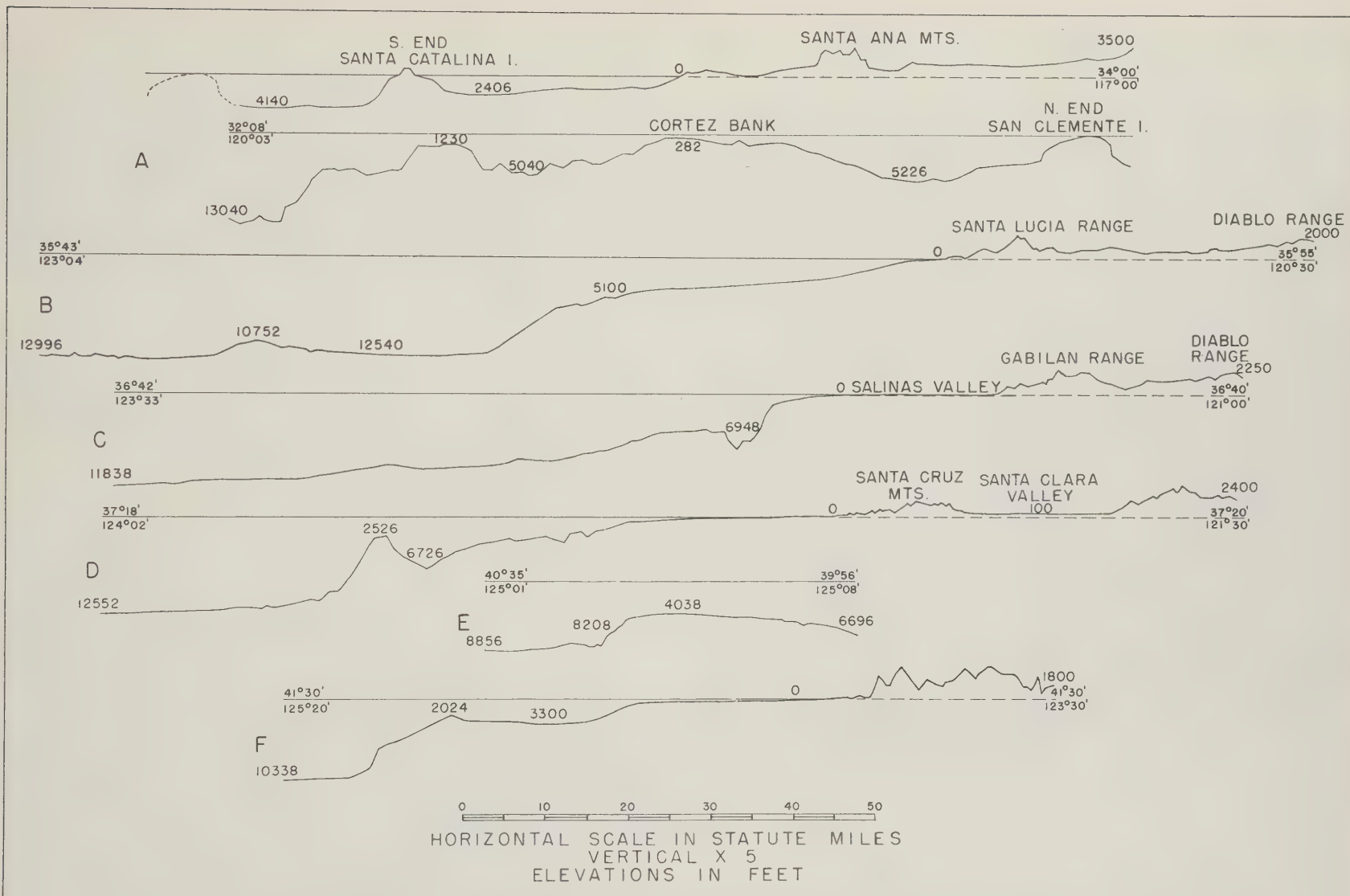


FIG. 149. Profiles at various latitudes along the California coast showing both surface and submarine features. Section A is in two parts. Depths from U. S. Coast and Geodetic Survey. After F. P. Shepard and K. O. Emery.



SPENCE
Air Photos

FIG. 150. A small sea stack at Morro Bay along the San Luis Obispo coast. Stack has been tied to land by a sand bar formed by wave action. Beyond island is a bay bar which shuts off the bay except for a narrow channel near the island. *Photo by Spencer Air Photos.*

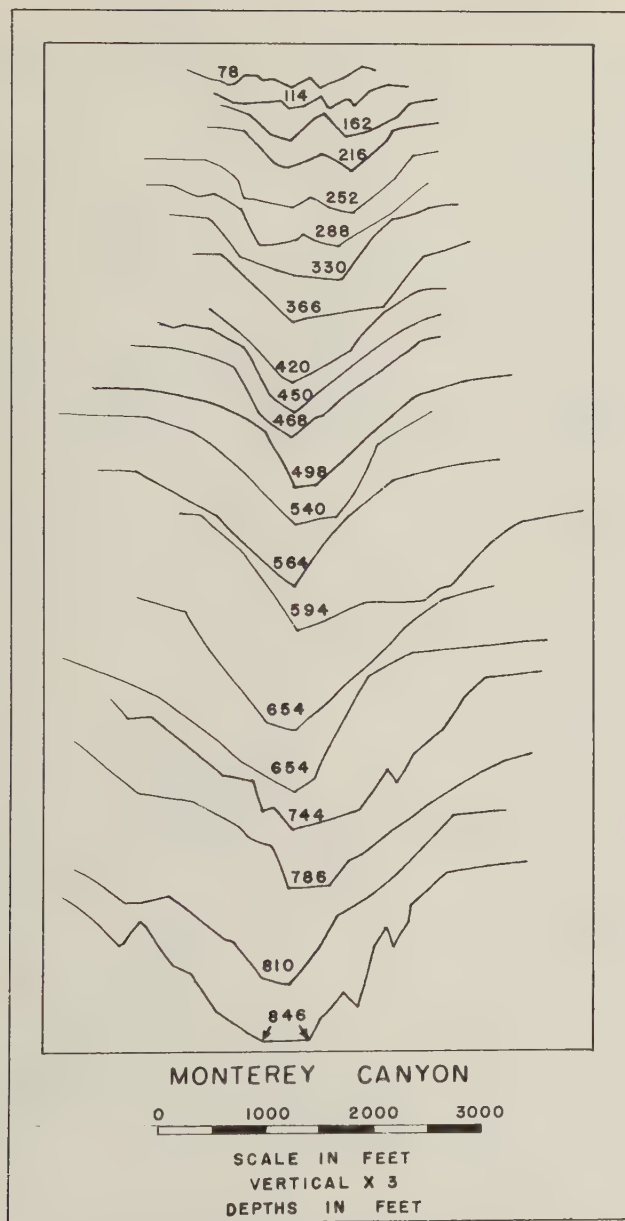


FIG. 151. Cross sections across the headward portion of Monterey submarine canyon. Depths from soundings by U. S. Coast and Geodetic Survey. After F. P. Shepard and K. O. Emery.

relation. The origin of these so-called *submarine canyons* has been much debated but as yet no satisfactory explanation has been advanced.

In the southern section of the continental borderland, most of the submarine canyons found along the coast do not extend to very great depths. Many are found where the scarps are offset or where the trend of an escarpment changes, but some are located in different settings.

From Point Conception to Cape San Martin, the submarine landscape is strikingly contrasted with that farther south. Except for one extensive valley and the gap which it forms in the continental slope, this section is relatively featureless.

Between Cape San Martin and Point Año Nuevo north of Monterey Bay, there is the greatest concentration of submarine canyons along the California coast and the canyons are the largest. Furthermore the gently sloping continental shelf and the long rather straight escarpment of the continental slope so prominent farther south are missing. The slope is much broken, not particularly steep, and is cut by many of the canyons.

In this section there are short canyons extending not far out beyond the shore line, while others are much deeper and break the continental slope, the hugest of the lot being Monterey Canyon, which may even extend beyond the margin of the continental slope into the floor of the deep ocean. The inner portion of this giant gorge can be compared with the Grand Canyon of the Colorado River in Arizona but the outer part is a broad trough with gently sloping walls. The gorge section is 50 miles long, the trough about 56 more.

South of Point Sur a fault extends to the coast and its seaward projection follows a submarine scarp which diverges southeastward from the coast. The group of submarine canyons in this section terminates headward along this structural line and two of the canyon heads appear to be deflected so that they parallel the supposed fault. This straight portion of the coast with mountains rising boldly above the shore line and a very narrow continental shelf possesses all characteristics essential to a fault coast.

Monterey submarine canyon and its tributaries also reflect structural features observed along the adjacent coast. Carmel Canyon, a large tributary coming in from the south, parallels the coast, and either is cut along a fault or in relatively weak rock between adjacent resistant materials. Beyond the deep part of Monterey Canyon, the broad trough previously mentioned extends seaward for about 22 miles. North of Monterey Bay the submarine canyons also terminate in a similar trough. The origin of these broad troughs is not known.

Beyond the slope off the southern part of this section a submarine mountain named Davidson Seamount, 16 miles long, 7 miles wide, and rising 7,000 feet above its 2-mile deep ocean base, is comparable with

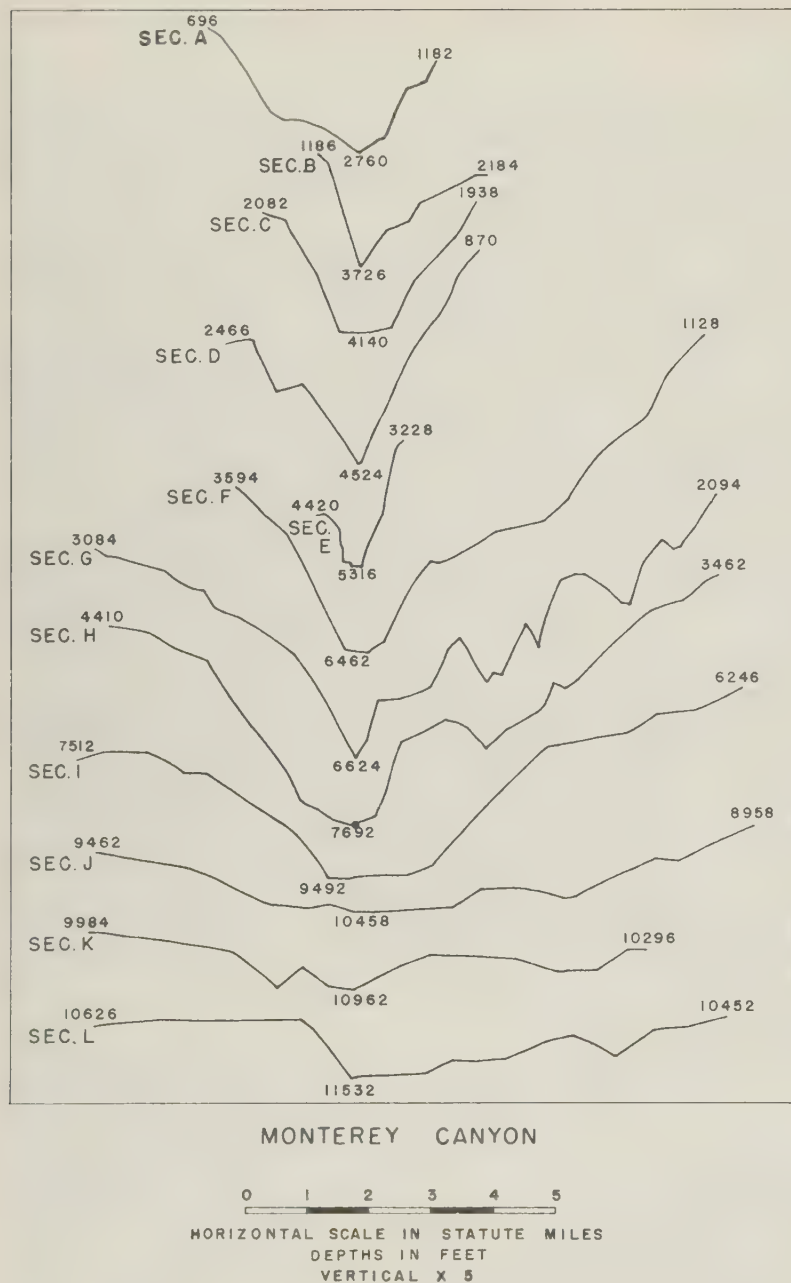


FIG. 152. Cross sections along middle and outer parts of Monterey submarine canyon. Sections J, H, and L show the trough-like character of the outermost part of the canyon. Depths by U. S. Coast and Geodetic Survey and Scripps Institute of Oceanography. After F. P. Shepard and K. O. Emery.

San Juan Seamount in the southern section first described. It has three or more peaks and two or three apparent depressions in its summit, which are about 500 feet deep and are believed to be craters. Davidson Seamount like its counterpart farther south is probably a volcano.

Northward between Point Año Nuevo and Shelter Cove, the submarine canyons start well out to sea and are largely confined to the continental slope. This section includes the San Francisco area where the shallow continental shelf extends outward for 25 miles, the greatest distance along the entire west coast of the United States, though considerably less than off the east and south coasts.

The great marginal scarp descending to the deep ocean is less sharply defined for there is a series of slope changes such as are found in the section immediately to the south. In the outer slope there are many canyons some of which may extend as deep as 12,000 feet. Southwest

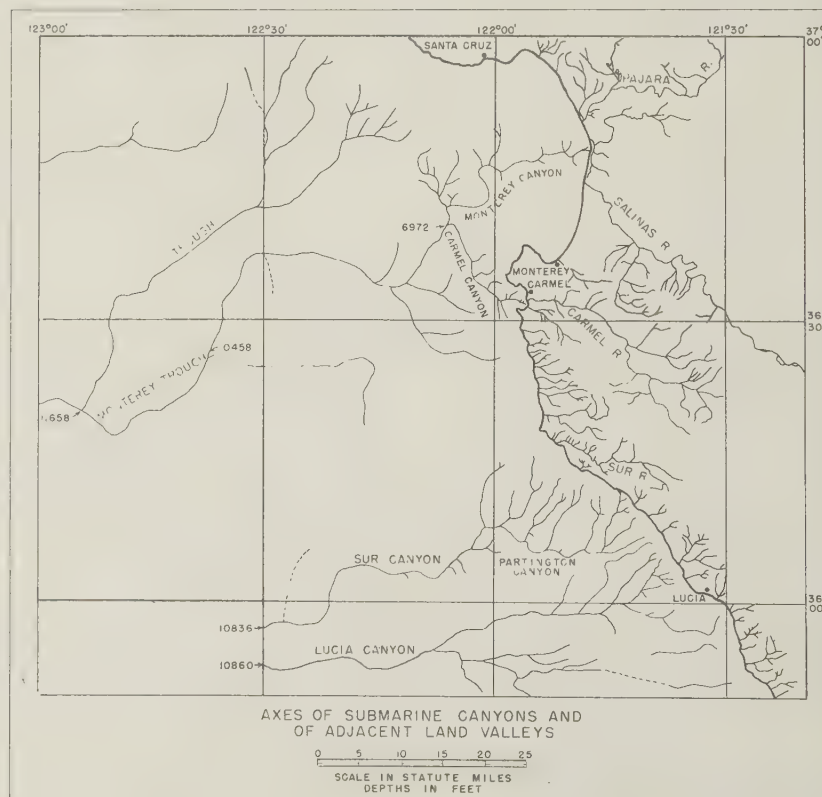


FIG. 153. Map showing relation between land rivers and submarine canyon axes off the coast in the Monterey Bay area and along the front of the Santa Lucia Mountains. After F. P. Shepard and K. O. Emery.

of the Farallon Islands, two mountains, which have been called Guide and Pioneer seamounts rise about 3,000 feet above their surroundings at the base of the continental slope. Possibly they are volcanoes.

Between Shelter Cove and the Eel River, the chief feature is a prominent submarine escarpment, called the Gorda or San Andreas, which extends for about 70 miles from Point Gorda. This zone also is notable for its large submarine canyons some of which extend almost to the coast.

The Gorda submarine scarp runs almost due west and except in one place is comparatively straight. Its height varies from zero at the edge of the narrow continental shelf to about 6,000 feet 30 miles out to sea. Beyond this point, the height decreases to about 4,000 feet at a distance of 60 miles from where it starts. Possibly the scarp continues farther out to sea though the indication is strong that it dies out within the next 20 miles. Along most of its length this imposing declivity is topped by a narrow ridge which has a series of summits rising to within 1,200 feet of the ocean surface, but beyond these hills the ridge broadens and is covered by water reaching 4,800 feet in depth. Along the north base of the ridge, there is a long, narrow depression or series of depressions.

The structure along the Gorda escarpment appears to be far from simple, but evidence now available is insufficient to give a very complete picture. The escarpment is unique not only for California, but for the world, since no place is known where there is a similar declivity running normal to the general trend of a coast. Epicenters of earthquakes have been located in the general vicinity of the scarp suggesting possibly that it is still forming.

The San Andreas fault has been traced as far as Point Arena, but beyond that there is difference of opinion regarding it. Some say it goes out to sea, while others believe that there is a return to the coast at Shelter Cove and an extension inland beyond that point. The evidence for the extension as far as Shelter Cove came from the development of a rift at that locality at the time of the 1906 earthquake. One authority holds that there are two faults beyond this point, one extending north-northwest to the coast at the mouth of Humboldt Creek and the other paralleling it about 2,000 feet inland. The rift noted above still is plain and can be traced across Point Delgada to the coast on the northwest, and from there about half way between Points Delgada and Gorda. About half way between these two coast prominences there is another riftlike feature. Toward Point Gorda the broken zone is less conspicuous but the formations are much contorted. The presence of a fault along the coast also is indicated by the way the structural features are cut off at the coast rather than being traceable in the topography of the adjacent sea bottom. Also Delgada submarine canyon heads against a steep ungullied mountain side while most others are located off land valleys or lowlands, suggesting a shift in the position of this canyon by horizontal movement such as

has been characteristic of the San Andreas fault. At the head of Delgada Canyon is a straight escarpment sloping at 45 degrees which also suggests faulting. All of this evidence indicates that the San Andreas rift extends along the coast almost as far as Point Gorda and if so, it should extend out to sea nearby. The great Gorda submarine escarpment previously described therefore may be the seaward prolongation of the San Andreas fault.

The zone off Cape Mendocino is broken by submarine canyons some of which are very large. One to the south can be traced seaward for more than 40 miles and to depths of more than 9,000 feet, while others have been followed 2,000 and 3,000 feet below sea level. North of the Gorda scarp, the canyons are related to land valleys, as for example the large ones in the area off the mouths of the Eel and Mattole Rivers.

From Eureka beyond the Oregon boundary, there are few submarine canyons or other spectacular topographic features.

It is noteworthy that on either side of the three most pronounced breaks along the California coast Point Conception, Monterey Peninsula, and Cape Mendocino are the largest submarine canyons. To a lesser degree the short canyons of the southern California coast can be related to projecting points of land, but in no case, either with major or minor projections, are the canyons located directly off the points. Submarine canyons are particularly rare in the steepest escarpments especially where the escarpments are topped by ridges, and they are almost as rare in the gently sloping portions of the continental shelf and the smaller banks.

If the principal tributaries are included, the number of known submarine canyons along the California coast is about 66, of which 18, including most of the larger ones, head within half a mile of the shore line. The other 48 start between half a mile and 30 miles from the coast with most between 3 and 5 miles. The gradients or slopes of the canyon floors are rather high, comparing with those of land canyons cut into mountain ranges or fault scarps, and there does not seem to be any serious interruption in this steepness at least to depths of 6,000 feet. The cross sections of the gorges are V-shaped in all but the deeper portions where some apparently widen into or are tributary to flattish troughs.

Dredging and coring operations have been carried on in 21 of the California submarine canyons and rock has been discovered in the walls of 17 of these; in only one, Newport Canyon, has this work been carried on sufficiently to make reasonably certain that solid rock is not present. Most of the rock obtained is soft Tertiary material some of it little more compacted than recent sediment, but in some places limestone, compact sandstone, and conglomerate have been found. Near the head of Dume Canyon of Dume Point in the Santa Monica region basalt was obtained from the head of the canyon which corresponded with basalt exposed on the point above sea level. Santa



FIG. 134. Distribution of fault scarps along the sea floor off the California coast. The directions of fault movement indicated are not positively established. After F. P. Shepard and K. O. Emery.



FIG. 155. Aerial photograph of South Farallon Island. Marin County shore line in distance; June 1949. Sea Lion or Saddle Rock is in the foreground. The rock of the Farallon Islands is granite. *Photo courtesy U. S. Coast Guard.*

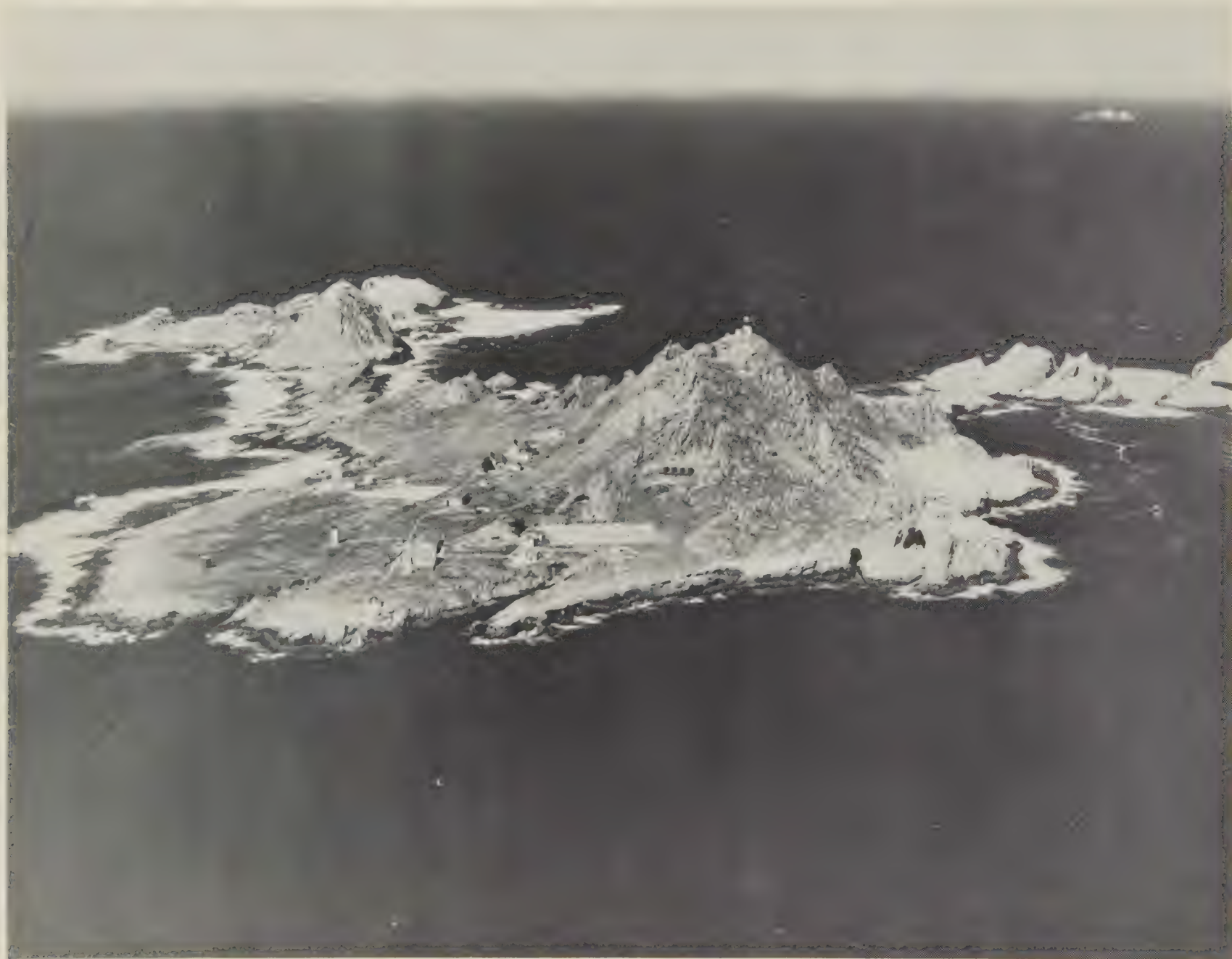


FIG. 156. Aerial photograph of South Farallon Island. Middle Farallon in the distance; June 1949. *Photo courtesy U. S. Coast Guard.*

Monica Canyon may be cut in granite though the evidence is not positive. Carmel Canyon is quite certainly cut in granite and a steep wall along Monterey Canyon showed the same rock to a depth of 3,900 feet. In three places resistant rock was met on one side of the canyon while the other was composed of unconsolidated sediment.

Submarine canyons in sea floors where large quantities of sediment are being deposited must mean either that the canyons have been very recently depressed below sea level or some process operates below sea level to keep them open.

The explanation of these remarkable submarine gorges has been actively debated. Some hold that they are river canyons which have been submerged below sea level either by the notable sinking of sections of the land or eroded during much greater sinking of sea level in the Pleistocene glacial stages than most authorities admit. Others believe that they have been formed by some type of crustal deformation, by the work of submarine currents or submarine springs, by landsliding, or by the occasional disturbances of the ocean when violent undersea earthquakes occur. No single process so far suggested explains the excavation of these gashes in the ocean floor, and this is to be expected for few geological features are simply evolved. Whether the complete answer to the question of the origin of the submarine canyon will ever be obtained is a matter of considerable doubt because of the difficulties of undersea exploration and the fact that direct observations are impossible.

The greatest scarp along the California coast is the continental slope which separates the deep ocean basin from the continental shelf in the northern area and from the continental borderland in the southern section. This escarpment is continuous along practically the entire California coast and may also extend off that of Lower California. It is offset in certain places. Near Point Conception the scarp is set shoreward but after about 30 miles it returns to the general position. In other places the north side is set shoreward apparently by dislocations along cross faults but without return to the general position as at Point Conception. However, in spite of the offsets, the continental slope comes back in line with the same gently curving trend which shows off southern California.

The structural trends offshore are not only shown by fault scarps but also by submarine ridges. The general north-northwest trend characteristic of the coastal ranges of California is well shown in various parts of the sea floor, while the east-west cross trends in the Los Angeles-Santa Barbara region also are expressed by east-west trends in the adjacent sea bottom.

Farallon Islands

Lying about 30 miles offshore from the Golden Gate are the small Farallon Islands which are clearly visible from the hills round about San Francisco Bay on a clear day. The group includes seven islets: the largest, South Farallon and a few nearby rocks; Middle Farallon, about two and a half miles north of South Farallon; and North Farallon, which are five rocks about 5 miles still farther northwest. Beyond North Farallon are Noonday Rock which is almost awash and Cordell Bank submerged under 20 fathoms (120 feet) of water. All of these units form what is called by some the Farallon Ridge running parallel to the shore line from the vicinity of the Golden Gate to Point Reyes.

On South Farallon is an important lighthouse originally established probably between 1852 and 1855. During the early part of the last century great numbers of fur seals and otters were caught on and around the islands and immense quantities of bird eggs were gathered and sold on the mainland. The latter activity was ended in 1909 when the islands were made a bird refuge now under the jurisdiction of the U. S. Coast Guard.

The Farallons are composed of granitic rock which is deeply weathered at the surface. The rock is broken by many joints and probably by faults whose most conspicuous trend is northwest-southeast. Many channels have been worn by wave attack along these fractures. A little west of the center of South Farallon, two of these channels meet from opposite sides at high tide dividing the island into eastern and western parts; this gorge is called the Jordan River. The amount of rock removed by wave attack in these channels testifies to the power of the waves as they sweep in and out, abrading the rock with the sediment which they transport and knocking out joint blocks as the waves dash against the rocks.

Wave-cut terraces are conspicuous on the South Farallon, standing about 50 feet above sea level. The buildings of the Coast Guard are located on one and another is at the west end of the island. Where the terraces join the higher parts of the island at the base of original cliffs eroded by the waves, there are elevated sea caves and surge channels like those along the present shore.

Nothing is known as to the nature of Middle and North Farallon.

REFERENCES

- Lawson, A. C., The continental shelf off the coast of California, National Research Council, Bull., vol. 8, pp. 3-23, 1924.
- Shepard, F. P., and Emory, K. C., Submarine topography off the California coast, Geol. Soc. America, Spec. paper 31, 1941. On pp. 161-166 of this monograph is an extended list of articles dealing with the subject.
- Hanna, G. D., Geology of the Farallon Islands: California Div. Mines Bull. 154, p. 301-310, 1951.

ADDENDA

COAST RANGES

San Jose-Mount Hamilton District *

The topography of much of the Coast Ranges is vigorously youthful, that is, the canyons are deep and rather narrow and there is little or no flat land along their bottoms. The streams are cutting downward. In some parts, however, the landscape has reached late youth or early maturity with the streams widening the lower parts of their valleys which have flattish surfaced alluvial fills. The canyons also have widened out considerably. Thus erosion and deposition may be going on along the same drainage system. In the San Jose-Mount Hamilton district, the more advanced phase is met, though the development is far from uniform throughout the area.

The cutting of canyons and their headward growth is the principal feature of the present erosion cycle, but there is clear evidence in various places of an earlier phase of canyon erosion which is indicated by decreases in slopes along the canyon walls.

From evidence which has been recently gathered, it appears that the mountains of the district have been elevated twice in rather recent geological time. The older of the two surfaces mentioned above seems to have been a canyon complex though the valleys were shallower and wider than those now being developed. Their bottoms stand about 1,000 feet above the bottoms of the new gorges. Standing still higher, up to 1,500 feet above the floors of the late canyons, is an older surface which appears to have been a gently rolling late mature or perhaps old landscape which is represented by extensive areas into which the canyons are cutting.

Healdsburg District †

A report published after this manuscript was written gives a brief account of landscape evolution in the Healdsburg district of the northern Coast Ranges.

It has long been recognized that the ridge crests of this region and farther north into the Klamath Mountains stand at roughly similar elevations above sea level, though the elevations change from one locality to another. Such ridge crests are said to be *accordant*. It has been believed that they represent residuals of an ancient surface which was elevated during the rise of the Coast Ranges during Pleistocene time. Between Healdsburg and the coast, the dissected surface of the Mendocino Plateau or Mountains is between 1,900 and 2,200 feet above sea level; in other places it stands higher or lower even passing

below sea level. Whether the ridge crests actually represent the elevation of an old landscape is doubtful, for there may have been a general lowering of the divides between canyons as erosion proceeded. Certainly there are no flat-topped areas remaining which may be interpreted as residuals of the surface. Since the present landscape is a succession of ridges and canyons giving a mountainous rather than a plateau topography, it is quite probable that the ridge crests stand somewhat below the surface from which they have been cut, even though the ridges have maintained general accordance of crest level.

The surface of the Mendocino Plateau or Mountains was considerably warped by the deformation which elevated the Coast Ranges during middle Pleistocene time, hence it stands at distinctly different elevations in various parts of the region. Warping of ancient landscapes is a common feature of their deformation. The old, eroded landscape also is present in the Mayacmas Mountains which lie northeast of Alexander Valley.

The ancient landscape referred to above appears to have been developed by late Pliocene time. While in general it was a surface of quite low relief, there were gently sloping hills which rose above broad valleys. There is a series of well developed river and marine terraces in the area which indicate that the uplift was spasmodic as always is the case. Some of the later terraces certainly were developed after the principal deformation closed.

Russian River. The Russian River is the largest drainage line in the Healdsburg area and one of the most important in the northern Coast Ranges. Its course through the ranges is striking and its history is complicated because of the series of events which has occurred since the river started to flow. The lower Russian River cuts across the Mendocino Mountains in a deep, narrow canyon; in this section the river appears to be *antecedent*, that is the drainage existed before the mountains rose and was able to maintain its course across them because the rate of uplift was matched by the rate of erosion of the cross canyon. The long section of the river stretching northward from the Llano de Santa Rosa probably is *subsequent* for it follows a zone of faulting which parallels the trend of the ranges.

Before the uplift of the Mendocino Mountains, the Russian River was a *consequent stream* which developed on the Mendocino block and flowed oceanward because the regional slope was in that direction. Other consequent drainage roughly paralleling the Russian River also is present. An example is the Navarro River which flows into the

* Crittenden, M. D., Jr., Geology of the San Jose-Mount Hamilton area, California: California Div. Mines Bull. 157, pp. 11-14, 1951.

† Gealey, W. K., Geology of the Healdsburg quadrangle, California: California Div. Mines Bull. 161, pp. 41-45, 1950.

Pacific Ocean from the crest of the Mendocino Range about 20 miles northwest of Healdsburg. The Navarro River is in direct line with a long valley trending southeast from the crest to join the Russian River. The latter segment also is in line with Big Sulphur Creek which flows into the Russian River from the southeast. At Yorkville there is a *windgap* between the valleys of Navarro and Big Sulphur Creeks indicating that the Navarro was beheaded by the extension of the Russian River in its subsequent section. A windgap is a short, abandoned gorge through which a stream formerly flowed.

Along the subsequent portion of the Russian River, wide valley sections are interspersed with narrow. In the Healdsburg district at least, it is evident that abnormal widths of the valley are controlled by the presence of weak strata in the deformed belt.

The curious passage of the Russian River through Sonoma Rock south of Jintown appears to have resulted from superposition, the

stream having been let down by erosion through a younger landscape into one more ancient.

The winding path of the Russian River through the canyon between Alexander Valley and Healdsburg again is the result of the structural control of its course. Also the prominent curves in the river between Wilson Grove and Guerneville probably are controlled by structure.

The last erosion level which carries across wide valleys and far up tributaries is correlated with late submergence which drowned many valleys along the coast and created San Francisco Bay. This submergence may have been caused by subsidence, but more probably was the result of the rise of ocean level as the great ice sheets of the last glacial stage diminished in size or disappeared. More recently there seems to have been slight uplift or sinking of ocean level for the river has cut from 20 to 25 feet into its deposits. This may be associated with some increase in volume of ice stored on the earth since the end of the Climatic Optimum.

INDEX

A

Abert Lake, 80
 Adobe Valley, 76
 Afton Basin, 89, 91
 Agua Caliente, 197, 200
 Springs, 107
 Alabama Hills, 64, 65 ✓
 Alameda Creek, 172, 176
 Alamo River, 103, 104, 108
 Alaska, 15, 27
 Aleatraz Island, 170
 Alder Creek Canyon, 121
 Alexander Valley, 230
 Alkali Lake, 83
 All-American Canal, 107
 Almanor, 55
 Alpine, 200
 County, 14
 Alturas, 111, 113
 County, 80, 81
 Amboy, 89
 American, 15, 18
 basin, 146, 147
 Canyon, 25
 River, 43, 52, 53, 147
 Amos, 99
 Anacapa, 189
 Angel Island, 170
 Antarctic, 27
 Anticline Ridge, 152
 Arbuckle, 147
 Argus Mountain, 74
 Range, 71, 75 ✓
 Arizona, 107, 223
 Arroyo Seco, 94
 Ashford Mill, 73
 Avawatz Mountains, 89
 Arenal Gap, 152
 Avondale, 210
 Awahnee Hotel, 30

B

Badwater, 72 ✓
 Bagdad, 89
 Bakersfield, 22
 Bald Peak, 176
 Baldwin Hills, 205
 Ballarat, 74
 Ball Mountain, 119
 Balloon Dome, 30
 Banner Canyon, 107
 Peak, 57
 Banning, 99
 fault, 203
 Barnard, 46
 Barstow, 91
 Basin-Ranges province, 9, 15, 19, 27, 63, 64, 76, 89,
 189
 Beacon Street, 204

Bear Butte, 127, 128
 Creek Canyon, 189
 foot Cave, 113
 paw Cave, 113
 River, 147
 Beaumont Plain, 203
 Benton-Bodie, 76
 Station, 76
 Berkeley Country Club, 176
 Hills, 164, 170, 172, 176
 Berryessa Valley, 164
 Beverly Hills, 205, 213
 Newport, 205
 Bighorn Plateau, 50
 Bigpine, 18, 64, 66, 68, 69
 Creek, 30
 Sulphur Creek, 230
 Tujunga River, 194
 Bullychoop Mountains, 141
 Birch Mountain, 19
 Bishop, 13, 63
 Creek, 19, 57
 Bixby slough, 204
 Black Butte, 122, 127
 Mountains, 72
 Range, 64, 71, 72
 Blue Lake, 86, 177
 Bluff Cove, 204
 Blythe, 94
 Boiling Lake, 131
 Bolam, 120, 127
 Creek, 128
 Bolinas Bay, 170
 Lagoon, 166
 Borax Lake, 179, 180
 Borego, 99, 200 ✓
 Valley, 107
 Boy Scout Hill, 132
 British Columbia, 15
 Brokeoff volcano, 131, 132
 Brown Mountain, 74
 Buckingham Peak, 177, 180
 Buena Vista, 152
 basin, 150
 Reservoir, 150
 Bullion Mountains, 89
 Bumpass Mountain, 132
 Buriburi Ridge, 164
 Burney Mountain, 119, 130, 135
 Burnt Lava, 82, 111
 Butte County, 147
 Creek, 121
 Valley, 119, 120

C

Cache Creek, 146, 177, 179, 180
 Canyon, 177
 Caibour Mountain, 139
 Cajon Pass, 185, 187

Calaveras Reservoir, 55
 Caldera, 80
 Caldwell Cave, 115
 California, 113, 185, 189, 206, 219, 220, 225, 229
 Coast, 27, 170, 172, 180, 194, 197, 219,
 223
 Ranges, 13, 139, 141, 152, 157, 177,
 180
 Development Company, 103
 Callahan, 111
 Camp Curry, 30
 Canada, 10
 Canada del Diablo, 186
 Canadian border, 119
 Canby, 111
 Cantua Creek, 150
 Cape Mendocino, 225
 San Martin, 223
 Captain Jack, 113
 Cargo Muchacho Mountains, 99
 Carmel Canyon, 223, 229
 Carpinteria plain, 187
 Carpo, 210
 Carquinez Canyon, 172
 Strait, 14, 145, 172
 Carson Range, 18, 21 ✕
 Valley, 18
 Carrizo, 99
 Creek, 99, 107
 Gorge, 107
 Cascade Gulch, 128
 Lakes, 41, 43, 55
 Mountains, 122, 128, 130, 139, 145, 146
 Range, 9, 111, 119, 120, 121, 129, 139, 145
 volcanoes, 122
 Cascadia, 15, 145, 157
 Castle Crags, 142
 Catalina, 194
 Island, 220 ✕
 Cathedral Rocks, 38
 Spires, 40
 Cedarville, 80, 83, 85
 Cenozoic, 10, 152, 157
 deposits, 73
 era, 17, 181
 Tertiary, 18
 time, 16
 volcanics, 139, 141, 145
 Central Plateau, 131
 Valley Project, 55, 139, 142
 Chagoopa Plateau, 50
 Chalk Mountain, 180
 Chalone Creek, 180, 181
 Valley, 180
 Channel Islands, 194
 Chaos Crags, 132, 134
 Jumbles, 132, 134, 135
 Chester, 130
 Chico, 146
 Creek, 147
 China Mountains, 139 ✕

- Chiquito Creek, 14
 Chocolate Mountains, 107
 Choyas Valley, 210
 Chula Vista, 210
 Cinder Cone, 127, 132, 134, 135
 Cirque Peak, 49
 summit, 47
 Claremont, 189
 Creek, 176
 Clark Lake, 200
 Clarksburg, 147
 Clear Lake, 86, 111, 113, 164, 177, 179 *x*
 basin, 177
 Climatic Optimum, 230, 232
 Coachella valley, 99, 100, 103, 203 *x*
 Coalinga, 152
 Coast Range belt, 141, 150
 Ranges, 9, 22, 47, 141, 145, 146, 157, 160, 164, 170, 230 *x*
 Coast Hills, 185
 Plain, 203, 204, 205, 206
 Cocopa Mountains, 108
 Cold Creek, 177
 Collins, 200
 Valley, 107
 Colorado, 103, 104, 106
 Aqueduct, 94
 Desert, 9, 89, 99 *x*
 River, 99, 103, 107, 108, 223
 Valley, 94
 Columbia plateau, 63, 111
 Colusa County, 147
 Condrey Mountain, 139
 Copco Dam, 121
 Lake, 121
 Cordell Bank, 229
 Cordonices Creek, 176
 Coronado, 206, 211
 Coronados Islands, 220
 Cortes, 220
 Coso Mountains, 69
 Range, 71
 Costa Mesa, 205
 Cosumnes River, 147, 150
 Cottonwood, 200
 Pass, 45
 Range, 107
 Coyote Canyon, 107
 Creek, 164, 185
 Hills, 205
 Wash, 206
 Cowles, 197
 Cracked Crags, 43
 Crater Lake, 219
 Basin, 132
 Mountain, 64, 68, 69, 119
 Crescent City, 139, 141
 Crater, 132
 Cretaceous, 10, 17, 141
 period, 22, 145, 157
 seas, 25
 time, 63, 157
 Crown Point, 211
 Crystal Cave, 115
 Springs, 164
 Cucamonga fault, 189
 Cuyamaca, 197
 Cuyamacas, 206
- D**
- Daggett, 89
 Dalton Canyon, 189
 Darwin, 47
 Hills, 71
 Wash, 71
 Davidson Seamount, 223
 Death Valley, 9, 27, 63, 64, 71, 72, 73, 74, 75 *x*
 Scotty's Castle, 73
 Deer Mountain, 120
 Delgada Canyon, 225
 Desert Center, 107
 Desolation area, 43
 basin, 43
 Lake, 53
 Valley, 41, 43
 Devil's Basin, 43, 53
 Golf Course, 73
 Kitchen, 131
 Postpile, 60 *x*
 Punchbowl, 80
 Diablo Range, 164, 172
 section, 147
 Dinkey Creek, 29
 Division Creek, 69
 Dominguez, 213
 Hills, 205
 Donner Lake, 53, 55 *x*
 Pass, 29
 Dos Palmas, 107
 Double Head, 111
 Drakesbad, 131
 Duck Flat, 83
 Dume Canyon, 229
 Point, 229
 Dunsmuir, 142
 Dwinell Reservoir, 121
- E**
- Eagle Lake, 86
 Peak, 31, 132
 range, 107
 Rock, 119
 Mountain, 119
 Eagleville, 85
 Lake, 85
 East Peak, 164
 Echo Lakes basin, 43
 glacier, 43
 valleys, 43
 Edgewood, 141
 Eel River, 225
- El Capitan, 31, 32, 38
 Cerrito Hill, 172
 Elk Valley, 166, 172
 El Paso Mountains, 89
 Portal, 31, 32
 Prado, 152
 Elsinore fault, 203 *x*
 Emerald Bay, 41, 43
 Eocene, 10, 18, 185
 epoch, 22, 23, 210
 Etna, 142
 Eureka, 141, 142, 225
- F**
- Fall Creek Mountain, 52
 Fallen Leaf, 41
 Lake, 55
 Fall River, 113
 Fandango Valley, 80
 False Bay, 206, 211
 Farallon Islands, 172, 229, 225 *x*
 Feather River, 15, 52, 145
 Fish Creek, 57
 Lake Valley, 69
 Mountain, 107
 Springs, 103
 School, 69
 Fort Bidwell, 85
 Friant Dam, 55
 Frink Spring, 103
 Fryxell, Fritiof, 19
 Funeral Ranges, 64, 71 *x*
 Furnace Creek, 72
 Inn, 72, 73
- G**
- Gabilan Mountains, 180
 Gaffey anticline, 204
 Street, 204
 Garlock fault, 75, 89
 Garner Mountains, 129
 Peak, 130
 Garnet Lake, 52
 Genoa Peak, 21
 Geysers, 131
 Gibson Peak, 139
 Gila River, 94
 Valley, 94
 Gilbert, G. K., 63
 Gilta, 141
 Glacial epoch, 18, 25, 26, 27, 29, 30, 57
 Glacier Peak, 122
 Point, 31
 Glen Alpine, 43
 Glendale, 189
 Glenn County, 146
 Godel Creek, 57
 Golden Gate, 27, 164, 170, 172, 229
 Canyon, 172
 International Exposition, 170
 Strait, 172
 Gold Lake, 52
 Goler Well, 89

Goose Lake, 63, 145
Valley, 82
Goosenest, 119
volcano, 120
Gorda, 225
Graben, 19
Granada Ranch, 121
Grand Canyon, 223
Granite Creek, 14
Grant Lake, 78, 79
Grapevine Canyon, 107
Ranges, 64, 71
Grass Lake, 43
Gray Butte, 122, 128
Great Basin, 89
Plains, 13
Valley, 9, 13, 14, 22, 25, 47, 142, 145, 150, 152,
157, 170, 172
Western Divide, 45, 51
Greenland, 27
Grizzly Peak, 129, 130, 176
Groundhog Cone, 57
Guatay Mountains, 200
Guerneville, 230
Gulf of Lower California, 99, 103, 108
Gull Lake, 78, 79
Guyot Flat, 49

H
Haight Mountain, 129, 120
Half Dome, 30, 31, 40
Moon Lake, 43
Valley, 43
Hall Canyon, 187
Harkness volcano, 131
Hat Creek, 131, 134, 135, 136
Hays Canyon Range, 82, 85, 111
Hayward, 176
fault, 170, 176
rift, 176
system, 176
Healdsburg, 230
Heather Lake, 43
Hemet Valley, 107
Hetch Hetchy Reservoir, 55
Valley, 40
High Rocky Lake, 83
Valley, 179
Hitchcock summit, 47
Hockett Peak, 30
Hollister, 180
Hollywood, 193
Honey Lake, 18, 86
Hoopa Valley, 142
Hoover Dam, 94, 106
Hornbrook, 141
Horn Canyon, 185
Horse Camp, 128, 129
Peak, 129, 130
Horsethief Butte, 120
Ranch, 120
Hotlum, 127
glacier, 128

Hotel del Coronado, 211
Howard Peak, 177
Humboldt Creek, 225
Humphrey Basin, 53
Hungry Hollow Hills, 147
Huntington Beach, 213
Mesa, 205
Hyampon, 142

I
Idaho, 82, 111
Igneous rocks, 17
Ikes Peak, 119
Illilouette Creek, 52
Imperial-Coachella, 197, 200
trough, 99, 106
Valley, 94, 99, 103, 104, 107, 108
Inconstance Creek, 128
Independence, 19, 68
Lake, 53
Indian Butte, 111
wars, 113
Wells, 100
Valley, 75
Indio, 100
Hills, 99, 107
Inglewood, 205, 213
Inspiration Point, 204
Inyo Mountains, 57, 69
Range, 69
-White Mountains, 64

J
Jackson, 55
Jack's Peak, 43
Jacumba, 200
Jess Lake, 86
Valley, 83, 86
Jimtown, 230
Johannesburg, 89
June Lake, 76, 78, 79
Jurassic, 10, 15, 16, 17
fold-faulting, 23
Mountains, 157
period, 15, 17, 157
strata, 139, 141, 142, 145
time, 57

K
Kane Spring, 100, 103
Kaweah Basin, 30, 51
group, 45
River, 15, 52
Kegg, 120
Kelseyville, 177
Kennedy Canyon, 185
Kern, 57
basin, 51
Canyon, 25
Lake, 55
River, 14, 15, 22, 29, 45, 49, 150
Canyon, 22, 30, 45, 46, 47, 50, 51, 55
Kettleman Hills, 152
Plain, 152

King Canyon, 25
City, 180
King's Basin, 51
Creek Valley, 131
River, 15, 29, 45, 52, 145, 150
area, 30
Kingston Ranges, 89
Klamath, 139
area, 141
Falls, 111, 113
Mountains, 9, 16, 55, 128, 139, 142, 145,
157, 230
region, 139, 141, 142
River, 121, 139, 141
Valley, 120
Klinker Mountain, 75
Koip, 47
Konocti, 177
Konwakitaon, 127
Kuna, 47

L
La Cima, 152
Cienega Boulevard, 213
Laguna Dam, 94
Mountains, 107, 213
La Habra Basin, 206
Jolla, 206, 210, 211
Lake Annia, 83
Cahuila, 103, 107
City, 85
County, 177
Manix, 89
Merced, 166
Russell, 76, 80
Tahoe, 9, 13, 14, 18, 21, 29, 41, 43, 55, 63
Pyramid Peak, 13
Yosemite, 32
Landing Hill, 205
Langley, 13, 46
La Posta valley, 200
Las Choyas, 211
Lassen County, 80, 111
Dome, 134
Park, 127
Peak, 132, 134, 135
Volcanic National Park, 130, 131, 136, 181
Last Chance Mountain, 64
Laurel Canyon, 193
Lava Beds National Monument, 111, 113, 129
La Verne, 204
Leach Point Mountains, 89
Le Conte Divide, 45
Leevining, 78
Canyon, 76
Liberty Cap, 30
Gap, 172
Liebre Mountains, 89
Linda Vista Mesa, 206, 210
Lintpuash, 113
Lion Mountains, 186

Little Deer Mountain, 120
 Glass Mountain, 129, 130
 Kern canyons, 57
 Merced Canyon, 30
 Red Cones, 57
 Shasta Valley, 120
 Tujunga River, 194
 Whitney Creek, 57
 Meadow, 57
 Yosemite canyon, 38, 55
 Valley, 32, 40

 Livermore, 176
 Valley, 164
 Llago Creek, 164
 Llano de Santa Rosa, 230
 Lone Pine, 13, 47, 66, 67
 Peak, 13, 49
 Long Beach, 185, 203, 213
 Harbor, 213, 215
 Point, 204
 Valley, 82, 83, 185
 Loon Lake, 52
 Los Angeles, 9, 16, 76, 185, 189, 197, 206, 213
 aqueduct, 63
 basin, 193
 region, 94
 River, 193
 -Santa Barbara region, 229
 Gatos Creek, 145, 150
 Lost Hills, 152
 Creek, 131, 132, 134
 Lake, 86
 River, 113
 Lover's Leap, 43
 Lower California, 15
 Klamath Lake, 111, 113
 Lake, 85

M
 Madeline Plains, 80
 Magee Mountain, 135
 Malaga Cove, 204
 Mammoth crest, 52
 Mountain, 52, 57
 Pass, 57
 Manitoba, 10
 Manix, 91
 Manly Lake, 73
 Manzanita Lake, 130
 Marble, 139
 Fork, 30
 Maria Mountain ranges, 94, 107
 Marin Block, 166
 County, 170, 176
 peninsula, 164, 166, 170
 Marysville, 145, 148
 basin, 147
 Mason Valley, 107
 Matthes, Dr. F. E., 13, 19
 Mattole River, 225
 Mayacmas Mountains, 230
 Mecca Hills, 99, 107
 Medicine Lake Highland, 111, 113, 128, 129, 130

Melrose Avenue, 213
 Mendocino Mountains, 230
 Plateau, 164, 230
 Range, 164
 Merced Canyon, 40
 River, 32
 canyon, 30
 Valley, 164
 Mesa Valley, 210
 Mesozoic, 10, 139, 141
 Mexican border, 99, 104, 107, 185, 197, 206, 210
 Mexico, 96, 99, 103
 Middle Creek, 177
 dome, 152
 Farallon, 229
 Fork, 14, 15, 30, 52
 Canyon, 60
 Kern River, 57
 Lake, 63, 83, 85
 Mid-Pleistocene, 157, 160, 164, 170, 204, 210
 Mill Creek Canyon, 86
 Millerton Lake, 55
 Miller Mountain, 119
 Road, 119
 Mill Valley, 131
 Mineral, 130
 King, 45
 Miocene, 10, 18, 23, 113, 205
 epoch, 157
 late, 25
 -Pliocene, 21
 strata, 93
 time, 19, 23, 50, 141, 157, 181
 valley, 25
 Miramontes, 166
 Mirror Lake, 32, 55
 Mission Bay, 206, 211
 Beach, 211
 Modoc, 111
 County, 80, 82
 Indians, 113, 145
 Modoc Lava Beds, 82
 Plateau, 135, 139
 Plateau, 9, 111, 113, 115, 129
 section, 63
 Mojave Desert, 9, 27, 63, 71, 89, 91, 99, 107, 189, 200
 River, 89, 91, 189
 Mokelumne, 15, 55, 147
 Mono, 14
 Basin, 76
 Cones, 181
 Craters, 79, 80
 -Inyo craters, 76
 Lake, 13, 14, 18, 27, 29, 52, 55, 57, 63, 76, 78, 79, 80
 Range, 57, 80
 Montara block, 166, 170
 fault, 166; Mountain, 164, 166
 Montezuma Hills, 146, 147
 Monterey Bay, 164, 170, 223
 Canyon, 223, 229
 Peninsula, 225

Monument, 115
 Monumental, 141
 Morena valley, 200
 Morgan Hill, 132
 Mormon Point, 73
 Mosquito Pass, 43
 Mossbrae Falls, 128
 Mount Baker, 122
 Brokeoff, 131
 Buckingham, 177
 Dana, 47
 Diablo, 176
 Eddy, 145
 Gibbs, 47
 Guyot, 50
 Hamilton, 176
 Range, 164
 Harkness, 132
 Helen, 132
 Hitchcock, 51
 Hoffman, 129
 King, 52
 Konocti, 177, 180
 Langley, 13, 47
 Le Conte, 51
 Lyell, 30
 Mallory, 51
 McAdie, 51
 McClure, 30
 Montgomery, 69
 Parker, 78
 Rainier, 122
 Ritter, 57
 Rose, 21
 Russell, 51
 San Antonio, 189
 Jacinto, 197
 Shasta, 9, 119, 120, 121, 122, 128, 129, 130, 181
 Tallac, 13, 21
 Tamalpais, 164
 Williamson, 13, 19
 Whitney, 13, 19, 25, 43, 45, 47, 49, 50, 51, 52, 65
 Wood, 78
 Young, 49
 Mud Creek, 122
 volcanoes, 107
 Muir, 45, 46, 47
 Crest, 51

Mc
 McCain Spring, 100
 Cains Plateau, 197, 200
 Cloud, 113, 127, 128
 Rivers, 139, 145
 Coy Mountains, 107
 Gavin Peak, 119
 Gee Canyon, 18
 Kittrick Hills, 150

N
 Napa, 164
 Navarro River, 230

INDEX

- Nestor, 210
 Terrace, 211
 Nevada, 71, 82, 94, 111
 border, 16, 76
 Falls, 38, 40
 Newark, 172
 Newport Beach, 205
 Canyon, 225
 -Inglewood, 193
 -Signal Hill, 213
 New River, 104, 108
 York-Providence Mountains, 89
 Niles, 176
 Noonday Rock, 229
 Nopah Ranges, 89
 Norden Station, 14
 North America, 13, 119, 219
 Butte, 148
 Chalone Peak, 180
 dome, 152
 Farallon, 229
 Fork, 15, 29, 52, 179, 180
 Island, 206, 211

 Oak Creek, 57
 Ocean Boulevard, 211
 Ojai, 185
 Basin, 185
 Valley, 186
 Old Dad Mountains, 89
 Baldy, 189
 Station, 136
 Town, 211
 Oligocene, 10
 epoch, 23
 Olympic Mountains, 14
 Oregon, 15, 80, 82, 111, 113, 119, 128, 139, 219, 225
 border, 139, 142
 Coast Ranges, 139
 Otay, 206
 Mesa, 211
 Mountains, 197
 Owens Lake, 14, 18, 19, 29, 63, 64, 67, 75
 River, 14, 63, 75
 Valley, 13, 18, 19, 27, 46, 57, 63, 64, 65, 66,
 67, 68, 69, 75, 76, 197, 206, 211

 Pacific basin, 16
 Beach, 211
 Coast, 16
 Ocean, 18, 157, 170, 172, 186, 193, 197
 shoreline, 206
 Pacoima Creek, 194
 Padre Juan Canyon, 186
 Pajaro River, 164, 170
 Palen Mountain, 107
 Paleozoic rocks, 139
 Palisade glacier, 30
 Palisades, 57
 Palm Canyon, 107
 Springs, 99, 197, 203
 Station, 107
 City, 211

 Palomar, 200, 206
 Mountains, 213
 Palo Verde Mesa, 94, 108
 Mountain ranges, 107
 Valley, 94, 108
 Palos Verdes Hills, 194, 203, 204, 213, 220
 Panamint Mountain, 64
 range, 63, 64, 71, 72, 75
 Valley, 27, 63, 64, 71, 75
 Panther Creek, 122
 Panum Crater, 80
 Paoha Island, 76
 Pardee Reservoir, 55
 Parker, 94
 Creek, 120
 Dam, 94
 Peak, 47
 Pasadena, 185, 189
 Peninsular Ranges, 10, 15, 197, 200, 206, 210, 213
 system, 197
 Petaluma, 164
 Creeks, 172
 Phillips, 43
 Pierpont Bay, 187
 Pillar Point, 166
 Pilot Knob, 94, 99, 103
 Valley, 75
 Pinnacles, 75
 National Monument, 180, 181
 Ranger Station, 181
 Pitas Point, 187
 Pit River, 86, 113, 130, 139, 145
 Valley, 82
 Playa del Rey, 213, 215
 Pleasant Lake, 52
 Pleistocene, 10, 18, 57, 119, 160, 229
 deformation, 157
 epoch, 71, 82, 205
 lakes, 180
 lava, 177
 mountain, 170
 rocks, 193
 sea, 205
 time, 22, 80, 119, 127, 141, 145, 185, 193,
 203, 204, 205, 211
 Pliocene, 10, 71, 72, 205
 -early Pleistocene, 19
 epoch, 18, 82, 130, 157, 193
 late, 25, 170, 204
 time, 18, 119, 129, 141
 Pluto's Cave, 120
 Point Año Nuevo, 223, 224
 Arena, 225
 Conception, 194, 223, 225, 229
 Delgada, 225
 Dume, 193
 Fermin, 204
 Gorda, 225
 Loma, 206, 210, 211
 Reyes, 170, 229
 Peninsula, 166
 Sur, 223

 Portuguese Point, 204
 Potrero, 213
 San Pablo, 172
 Poverty Hills, 64
 Poway Terrace, 210
 Prospect Peak, 131
 Puente Hills, 203
 Puerto Falso, 211
 Pumice Butte, 57
 Flat, 45, 57
 Pyramid Lake, 14, 63
 Peak, 43
 Range, 43

 Quail Mountain, 128

 Raccoon Pass, 172
 Strait, 170
 Rainbow Fall, 57
 Range, 99
 Raker Peak, 131, 132
 Randsburg, 75, 89
 Red Banks, 122, 177
 Bluff, 130, 145, 156
 Butte, 128
 Redding, 111, 113, 142, 145
 -Alturas road, 130
 Redlands, 185
 Red Mountain, 69, 132, 139, 185, 186
 Rock Island, 170
 Redwood Peak, 176
 Reds Meadow, 57
 Reno, 14
 Reversed Creek, 78, 79
 Creek-Rush Creek canyon, 78
 Valley, 76
 Rhett Lake, 113
 Ribbon Falls, 40
 Richardson Bay, 166
 Richmond, 176
 Coyote Hills, 172
 Rincon Mountain, 185, 186, 187
 Ritter Range, 44, 45
 Rising River, 136
 Riverside, 94, 185, 197
 Rockbound Basin, 43
 Valley, 43
 Rock Canyon, 51
 Rockies, 16
 Rocky Mountains, 13, 14, 119
 Rogue River, 141
 Rosecrans, 213
 Rose Valley, 64
 Russian River, 164, 170, 176, 230
 Round Tap, 176
 Valley, 19
 Royal Arches, 40
 Rubicon Peak, 21
 Rush, 78
 Creek, 76, 78, 79
 Russell, 46
 Russia, 10

Russian Peak, 139
 River, 164, 170, 172, 176, 230 X
 Rustic Canyon, 193

S

Sacramento, 14, 145, 147, 150, 152, 176
 Basin, 147
 Canyon, 128
 River, 127, 128, 139, 141, 142, 145, 146,
 164, 166, 170, 172, 176, 177
 Valley, 53, 130, 142, 145, 146, 147, 148

Saline Valley, 69, 219
 Salmon, 141
 Mountain, 141

Salton Basin, 103, 104, 107, 108
 Sea, 99, 100, 103, 104, 107, 108

Salt Wells Canyon, 75
 Valley, 75

San Andreas, 55, 89, 107, 160, 164, 189, 225 X
 fault, 176, 181, 203, 225 X
 rift, 166, 170, 176
 Springs, 164
 system, 176
 zone, 189

Antonio Canyon, 189
 Creek, 186

Bernardino, 185, 200, 205, 220 X
 County, 74
 Mountains, 71, 89, 99, 189, 200,
 205
 Range, 185, 203, 220

Borja, 197

Bruno fault, 164, 170
 Hills, 164
 Mountain, 164

Clemente, 194
 Island, 220

Sand Hills, 94, 99, 100

San Diego, 94, 185, 206, 210
 Bay, 211
 Mesa, 206, 210, 211
 region, 206
 River, 206, 210, 211

Dimas cove, 204

Felipe, 107
 Creek, 107
 Valley, 100

Fernando, 185, 204
 Valley, 193

Francisco, 157, 160, 164, 170, 176

Francisco area, 224
 bay, 14, 27, 55, 76, 145, 157, 164, 166,
 170, 172, 229, 230
 -Marin block, 170, 176
 Peninsula, 166

Gabriel, 189, 205 X
 Canyon, 189
 Mountains, 89, 185, 189, 204, 205
 Range, 189, 203, 230 X
 River, 204
 Valley, 204

San Gorgonio Pass, 99, 100, 107, 203
 Peak, 189

Jacinto, 99, 100, 107, 197, 200
 fault, 205
 Mountain, 197, 203, 220
 ranges, 203
 Santa Rosa mass, 197

Joaquin, 145, 146, 147, 152
 drainage, 51
 Mountain, 78
 River, 14, 15, 29, 30, 45, 52, 53, 57, 150
 Valley, 14, 22, 55, 150, 152 X

Jose-Mount Hamilton, 230

Juan Seamount, 220, 224

Mateo Point, 172

Miguel, 185, 189, 194, 197

Nicolas, 194
 Island, 220

Pedro, 166, 204
 Hill, 204, 205, 206
 Martir, 197

Quentin Point, 166

Rafael Mountains, 157

Ramon, 176, 164
 Valley, 176

Santa Ana, 205 X
 Creek, 185, 186
 Mountains, 197, 203, 220 X
 River, 189, 203, 205
 Valley, 185, 205

Barbara, 189, 194
 County, 157
 Island, 193, 194

Catalina, 220

Clara River, 185, 187
 Valley, 164, 170, 185, 186, 187 X

Cruz, 189
 Basin, 219, 220
 Island, 220
 Mountains, 164

Fe Springs, 205, 206
 -Coyote uplift, 206

Inez, 185, 200
 Mountains, 185, 186

Monica, 193, 205
 anticline, 193
 Mountains, 185, 189, 193, 194, 205,
 213
 Plain, 193
 Range, 193, 230
 region, 229

Paula, 185
 Creek, 185, 186

Rosa, 185, 189, 197
 Mountains, 99, 107, 197, 200

Susana Mountains, 193

Ynez Range, 185

Santiago Peak, 203

Sawmill Creek, 68, 69
 Mountains, 89

Scott, 139
 Creek, 177
 Market, 141

Scripps Institute, 210

Seacliff station, 187

Seal Beach, 213
 Rocks, 166

Searles Lake, 75
 Valley, 75
 Valley, 89

Secret Spring Mountain, 119

Sedimentary rocks, 17

Sennor Canyon, 185

Sentinel Dome, 31
 Rock, 38

Sepulveda Canyon, 193

Sequoia National Forest, 52
 Park, 45

Serra Cross, 187

Seventeen Palms, 99

Shasta, 121, 122, 127, 128
 County, 111, 141
 Dam, 55, 139, 142
 glaciers, 120
 River, 120
 Valley, 119, 120, 121, 128

Shastan activity, 127

Shastina, 121, 122, 128

Sheep Hole Mountains, 89

Sheller Cove, 224, 225

Shepherd Pass, 45

Shore Line Butte, 73

Siberia, 27

Sierra, 52, 150
 Buttes, 52
 -Cascade, 18
 Madre, 189
 Nevada, 9, 10, 13, 14, 15, 16, 17, 18, 19, 21,
 22, 23, 24, 25, 27, 29, 30, 43, 44, 45, 47, 50,
 51, 52, 54, 63, 64, 65, 67, 68, 69, 71, 75, 76,
 78, 79, 89, 119, 128, 130, 141, 142, 145,
 150, 157, 181, 197, 200, 219 X

Sierran bedrock, 78
 canyons, 32, 55
 crest, 25
 fronts, 65
 geology, 13
 lakes, 55
 landscape, 23
 region, 19, 46, 51
 scarp, 19
 slope, 18

Sierra Pelona, 89
 San Juan de Dios, 197
 Valley, 21

Signal Hill, 205, 213, 215

Silurian Lake, 89

Silver Lake, 52, 78, 79, 89
 Strand, 206

Simi Hills, 193

Siskiyou, 139
 County, 111, 113

Sixty-Lake basin, 52
 Slate Range, 74, 75, 89
 Soda Lake, 89
 Basin, 91
 Soledad Mountain, 206, 211
 Sonoma, 164
 Range, 164
 Rock, 230
 Soule Butte, 120
 Ranch, 120, 121
 South Butte, 145
 Chalone, 181
 dome, 152
 Southern California, 185, 203, 229
 Pacific Railroad, 14, 104
 Peak, 177
 South Farallon, 229
 Fork, 19, 30, 43, 57, 139, 141
 Island, 211
 Pacific Beach, 210
 Yolla Bolly, 139
 Spanish, 211
 discoveries, 103
 Spurr, J. E., 63
 Stanislaus River, 15, 52, 152
 Stockton, 152
 Stony Creek, 146, 147, 135
 Stovepipe Wells, 73
 Strawberry Creek, 176
 Subway Cave, 136
 Sugarloaf Mountain, 136
 Suisun Bay, 146, 147, 150, 172, 176
 Sulphur Bank, 179, 180
 Mountain, 185, 186
 Upland, 185
 Sunol, 176
 Superstition, 99, 103
 Surprise Valley, 80, 82, 83, 85, 86, 111
 Susie Lake, 43
 Sutter Buttes, 145, 148
 County, 147
 Swansea, 67
 Sweetwater, 211

T

Table Mountain, 47
 Taboose Creek, 68
 Tahoe, 78, 79
 basin, 21, 200
 fault basin, 43
 Tallac-Dick's Peak range, 41
 Tamalpais, 166
 Tamarack, 14
 Tanner Banks, 220
 Tecolote Canyon, 210
 Tehama, 146
 County, 139

Tehachapi Range, 145
 Pass, 13, 29
 Mountains, 89, 150
 Telescope Peak, 75 X
 Temescal, 193
 Wash, 203
 Tenaya Canyon, 30, 32, 38, 55
 Tennessee Cove, 166
 Terrace, 206
 Tertiary, 10, 63
 deposits, 74
 material, 225
 rocks, 72, 193
 sediments, 142
 The Gardens, 82
 Incomparable Valley, 19
 Minarets, 57
 Thompson Peak, 139
 Thousand Island Lake, 52
 Three Brothers, 31
 Thurston Lake, 177, 180
 Tia Juana, 210, 211
 Tiburon Peninsula, 166
 Timber Mountain, 111
 Tioga, 78
 Pass, 29, 63, 76
 road, 78
 Tokopah Valley, 30
 Toawa Range, 57
 Valley, 57
 Tomales Bay, 166, 170
 Topanga Beach, 193
 Transverse Range, 157, 185, 189, 194, 197, 200
 Ranges, 9, 10, 15, 16, 99
 Treasure Island, 170
 Triassic, 10
 strata, 139
 volcanics, 64
 Trinity Alps, 139 X
 County, 139
 Mountain, 141
 River, 141
 Trolleyway, 213
 Trout Creek, 57
 Truckee, 21
 Meadows, 19
 River, 14, 19, 21, 43, 63
 Canyon, 43
 Valley, 43
 Tueeulala Falls, 40
 Tuff, 204
 Tujunga Canyon, 189
 Tulare, 152
 Lake, 150
 Tule Lake, 111, 113
 basin, 111

Tungsten Hills, 64
 Tunnel, 57
 Tuolumne Canyon, 29
 Meadows, 55
 River, 15
 Twin Lakes, 55
 Tyndall, 46
 Creek, 50

U

Ubehebe Craters, 73 X
 Union Pacific Railroad, 89
 United States, 13, 14, 27, 72, 99, 100, 219, 224
 Coast and Geodetic Survey, 213
 Guard, 229
 Geological Survey, 13, 63, 213
 Navy, 215
 Weather Bureau, 13
 Upper Lake, 83, 85
 Merced Canyon, 32
 Uppermost Pleistocene, 185

V

Vallecito, 107
 Valley, 107
 Valle San Jose, 200
 Venice, 213, 215
 Ventura, 186
 County Courthouse, 187
 district, 185
 River, 185, 186, 187
 Valley, 186, 187
 Vernal Falls, 38
 Vicente Mountains, 193
 Viejas, 200
 Vina, 146
 Volcan, 200
 Mountain, 213
 Volcano Creek, 57
 Vulcan's Castle, 132

W

Walker River, 55
 Walnut Creek, 164
 Wallace Canyon, 51
 Creek, 50
 Warner block, 82
 Canyon, 82
 Mountains, 63, 80, 81, 82, 85, 86, 111, 145
 Range, 80, 82, 83, 85, 86
 Valley, 80, 107, 130
 Washington, 14, 15, 82, 111, 119, 122
 Column, 32, 38
 Weaverville, 142
 Weitchpec, 139
 Westgard Pass, 69
 Westmorland, 103
 West Peak, 164
 Whaleback, 119, 120

White-Inyo Mountains, 71
 Range, 63, 64, 66, 69
 Mountain, 131, 132
 Peak, 69
 Mountains front, 65
 Whitney, 46, 47, 127
 Canyon, 51
 Creek, 51, 128
 glacier, 121
 Hill, 47, 50
 Pass, 51
 region, 51
 Whittier, 204, 205
 Wildrose Canyon, 71
 Williams, 146, 147
 -Clear Lake, 180

Williamson, 46
 Willow Creek, 142
 Mountain, 119
 Willows, 146
 Wilson Grove, 230
 Wilson's Cove, 194
 Wingate Pass, 74, 75
 Winters, 147
 Wintun glacier, 128

Y

Yale University, 27
 Yellow Butte, 120
 Yerba Buena Island, 170
 Ygnacio Valley, 176
 Yolo Basin, 146, 147, 177

Yolla Bolly Mountains, 141
 Yorkville, 230
 Yosemite Canyon, 32
 Falls, 40
 glaciers, 29, 30
 landscape, 40
 National Park, 13, 29, 47, 76
 region, 30, 51
 -Tahoe region, 30
 Valley, 25, 31, 32, 38, 40, 52, 55
 Young summit, 47
 Yreka, 141
 Yuba Canyon, 25
 River, 15, 58, 146, 147
 Yuma, Arizona, 94, 99, 103, 107

